Telephone Systems

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Telephone Systems, Textbook

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INTRODUCTION

New technologies are developed every day in the world of communication. These new technologies require a continuous education. This is the fourth in a series of courses designed to give you a solid foundation upon which to base this education.

In *The Principles of Electronic Communication* course, you were introduced to the properties of audio-frequency signals, and the transducers that translate these signals to and from sound waves. Throughout the text you learned about the applications of signals in both audio systems and telephone systems. In the first section of this course, we focus upon the telephone and its operation in a local circuit to communicate voice information.

As a piece of electrical apparatus, the telephone set can be a very simple device with no electronic components, or it can be a sophisticated piece of electronic equipment, with extensive electronic circuitry. However, both the simple and the sophisticated telephone sets can identically connect to the same telecommunications system, and instantly transmit and receive information throughout the world.

In the second section of this course, we introduce the fundamentals of signal generation and the techniques and circuits used to generate audio and voice frequency signals. The instruction continues to describe the electrical properties of transmission lines and circuits, and how these principles are applied to telephone service. We also review the standard techniques used for measuring and quantifying the performance of telephone systems.

The third section describes advanced telephone systems. We describe key, PBX, and Centrex systems, and their main differences. We also explain how cellular telephones work, and introduce you to PCS, which is the newest cellular telephone technology.

COURSE OBJECTIVES

When you complete this course you will be able to:

- Name and explain the function of each part of a telest.
- Explain, in detail, the equipment used to complete a telephone call from a local subscriber to a distant, long-haul subscriber.
- Explain and calculate the electrical properties of transmission lines in units of R, L, and C.
- Describe the differences between key, PBX, and Centrex telephone systems.
- Describe the operation of a modern cellular telephone.

COURSE OUTLINE

Introduction

Section 1 — Telephone Fundamentals

Chapter 1 – Basic Telephone Service
- Introduction
- Objectives
- Overview of the Basic Telephone Service
- The Local Loop
- Signals and Signaling
- Sequence of Operation
  - Completing a Local Call
- Calling Beyond the Local Central Office
- Summary
- Self-Test Review

Chapter 2 – Telephone Equipment
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- Objectives
- The Telephone Set
- The Network
  - The Transformer Network
  - The IC Network
- The Dial
  - Tone Dialing
- Summary
- Self-Test Review

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  - Loading the Telephone Circuits
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  - Time Detection
- Summary
- Self-Test Review

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- Coaxial Cables
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  - Specifications and Measurements
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  - D-Type Compensation
  - Specifications
- Measurements
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Section 3 — Advanced Telelphone Systems

Chapter 7 – Business Telephone Systems
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- Key Telephone System
- Private Branch Exchange (PBX)
  - Digital PBXs
  - Wireless PBX
- Central Office Exchange (Centrex)
- Summary
- Self-Test Review

Chapter 8 – Cellular Telephones
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- Objectives
- History of Mobile Telephones
- How Cellular Telephones Work
  - Registration and Tracking
  - Placing a Phone Call
  - Roaming
- The Cellular Phone
- The Cellular Base Station
- Cellular Problems
- Personal Communications Service (PCS)
  - Description
  - Technical Aspects
  - Advantages of PCS
  - Disadvantages of PCS
  - Future Outlook
  - Recent FCC Action
- Summary
- Self-Test Review

Section 1

Telephone Fundamentals

CHAPTER 1 — Basic Telephone Service

INTRODUCTION

The telephone set is just *one* functionally simple part of a very complicated system of interconnection, transmission, and signal processing. The functional aspects of each *individual* part of the telephone system may be simple, but the combination of these parts complicate the system and its functions. Attempting to understand an entire telecommunications system in detail is, therefore, an overwhelming task. Taken individually, however, you can learn most *parts* of the system with ease. To keep things simple, and easier to understand, we will introduce only the *generalities* of the overall communications system in this text, and then concentrate on the individual *parts* of the voice telephone system in detail.

The telephone system is only one aspect of the more-comprehensive telecommunications technology that includes the communication of voice, data, and video signals. Telephone systems are primarily used for communicating voice and audio-frequency data signals, a service that represents only one aspect of telecommunications. The technology is in a continual state of transition, however, in response to the needs of a growing market for communication services. The telephone, and its local wired voice circuits are gradually assimilated into a more comprehensive service as shown in Figure 1-1.* Even with this change, however, the large number of existing telephones require service compatibility.

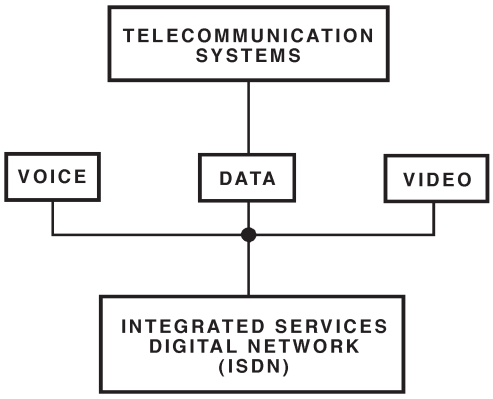


Figure 1-1

* The planned growth of telecommunications technology will gradually tie together all aspects of electronic communications within a single service. This comprehensive service is called the “Integrated Services Digital Network,” ISDN.

Throughout many decades of technological growth, much of the early telephone technology has been assimilated into modern electronic counterparts of early designs. This is necessary, because all of the telephones in the world must continue to talk to each other without disruption of service. With this criteria, advances in technology can *assimilate,* but not replace current telephone service. Be assured that your study of this service, and its operation, will remain as useful fundamental knowledge.

The major attribute of telephone systems is their ability to interconnect with the large number of terminals and circuits that are installed throughout the world. This extensive "installed base," with quick, cheap, and reliable access, makes the telephone system an important necessity of modern life. The real value of the telephone is, therefore, proportional to the number of other telephones to which it can be connected. The world-wide open-access networks of telephone service providers, and the large installed base of users, are what make the telephone a vital part of our daily lives.

Completing A Phone Call

The instructional content of this chapter first details the operation of the telephone set, the central office, the wired circuits, and the signaling used to operate the local telephone system. Later sections then describe the circuits which create and detect the signaling used in operating the system.

The telephone set, also referred to as a "telset", comprises transmit and receive transducers, a network to separate the transmit and receive signals, a dial pulser, a ringer, and a hook-switch. For operation, the telephone set must be connected to a source of power and a wired circuit that connects it to a central office. For most telephones, the power is provided by the central office, via the same two-wire lines that connect the telephone voice signals to the office.

The major purpose of the central office is to switch the many telephone calls (traffic) to and from their circuit paths. The central office also provides "talk battery" power, dial tone, ringing, and other signaling to the telset. The signaling complies with circuit path standards for the central office to function with the extended world-wide telephone network, as shown in Figure 1-2. With access to this network, the central office provides for interconnection of calls between other central and exchange offices, and it maintains usage data for the business operation of the service.

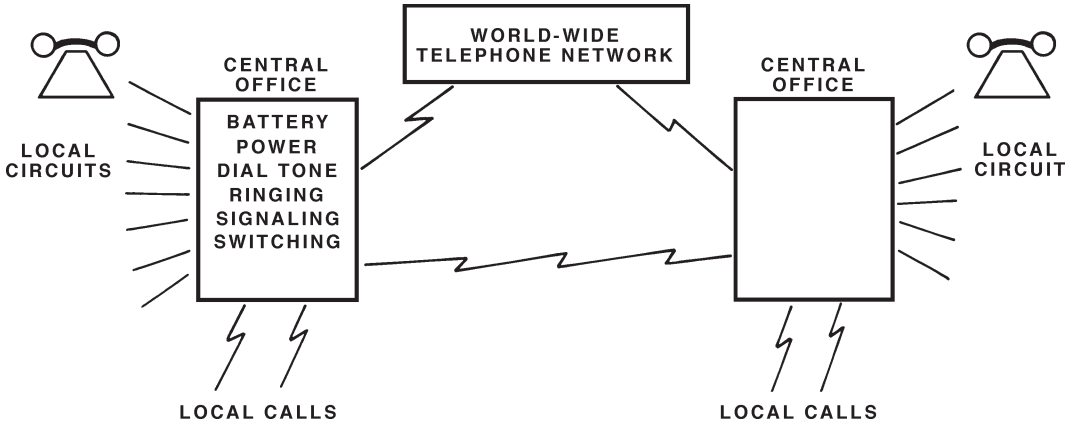


Figure 1-2

You originate a phone call when you lift the telephone's handset, which activates a dial tone from the central office. You then dial-up a sequence of numbers that accumulate in the storage circuits, in a dial address, of the central office switch. With a local call, from the same office, the switch selects the location where the wires connect to the party you are calling. A ring signal, from the central office, is then applied to that line, which activates the called party's ringer, and a separate ringback signal is applied to your line, to let you know that your called number is being addressed. When the called party lifts their handset, the switch connects your line with that of the called party to provide for two-way communication.

The word *"signal,"* used in telephone service, differs from our earlier technical definitions. Much of the terminology of the telephone originated in telegraph and visual communication, where to "signal" is used in the context of signaling someone, rather than describing an acoustical or electrical wave. When you lift the telephone handset, for example, the resulting current that flows through your telephone from the central office is a "signal." The dial tone is a "signal," ringback is a "signal," and a busy signal is a "signal." Signals in this context of signaling can take the form of tones, the presence or absence of currents, and/or the indication of circuit wire ground conditions.

By contrast, "voice signals," often called "messages," are the terms used to describe conversation or transmission of information. To keep terminology accurate in this text, we will attempt to maintain these distinctions, and always use the words "voice signals" when we are referring to information.

> The word "signals," as used in telephone service, identifies a *message* that is communicated, not an electrical wave. "Signaling" describes the tones and currents used to indicate system operation.

The central office's functions are activated by the special signaling that occurs from the actions or conditions of the called and calling parties, and from the actions or conditions of the central office switch. The central office switch serves local circuits only, but it also accesses other switches for long-distance circuits. The routing of traffic through other switches and other central offices is complicated, due to the millions of telephones and lines in use throughout the world. As with the local circuits, long-distance communication is managed through a number of special "signaling" signals that activate the system's proper operation. Signaling is, therefore, an important part of all telephone systems.

> The central office's functions are activated by "signaling" signals. These signals occur from the *actions* or *conditions* of the called and calling parties, and of the central office switch.

In this introduction, we have described the general structure and operation of the telephone system, and the functions used by the central office to complete telephone calls from one point to another. Probably the most important aspect of this introduction to the telephone system is exposure to the terminology and jargon of the telecommunications industry-

OBJECTIVES

When you complete this chapter, you will be able to:

- Define the distinctive vocabulary terms used in telephone practice, and relate them to electrical principles and terminology.
- Identify each of the signals and messages used to operate local telephone services, including those signals that originate in the telset, and those that originate at the central office.
- List the sequence of operations necessary to complete a local telephone call within a single zone of service.
- Identify the structure and service areas of the Public Telephone Network's digit dialing numbering plan.
- Specify the interconnect and switching hierarchy of the local exchanges and the long-haul network.

OVERVIEW OF THE BASIC TELEPHONE SERVICE

As noted in the Introduction to this chapter, the telephone, and telephone service are older technologies adapted to the complications of modern electronic systems. Telephone systems are in extensive use throughout the world, with public access for interconnection between all of the telephone sets connected to these systems. This interconnection of telephones, with access by almost anyone, is called the "Public Telephone Network" abbreviated PTN.

In addition to the PTN, there are also many *private* telephone networks in "closed-access" service to businesses and governments. To study each of the telephone services individually is impractical. However, there are few major differences in the operation of the services, and knowledge of one system can easily be applied to another. In this text, we will specifically describe the aspects of the largest of these services, the PTN.

To learn about the PTN and telephone practice, you must first learn to decipher the "mish-mash" of terminology, abbreviations, acronyms, and codes used to identify its operation and services. Like all specialized technologies, the telephone business has evolved its own "jargon." Learning this jargon is almost like learning a foreign language. If you relocate to a foreign country, you must learn a new language. However, language alone does not make you a part of a culture. To understand a foreign culture, you must first adopt the language, and then apply the concepts represented by the language. The same process applies to telephone practice.

As you study this chapter and those that follow we recommend that you write each new term, and its abbreviation or code when you first read it. Then, each time you see its abbreviation, read the full words and recall their meaning. Repeat this deliberate process until it becomes automatic, and the abbreviations convey the full meaning of the terms. As you proceed, keep in mind that the same concept is often identified in more than one way. For example, the telephone service provider, the telephone company that provides PTN services, is called "telco." List similar terms such as these also, to reduce confusion.

The common component of the telephone network is the telephone set, operating in conjunction with a wired circuit from a central office. The central office, or CO, is usually part of a larger telephone company identified as "telco." Telco offers services from its central office, via a wired circuit it calls "facilities," to terminal equipment, or station

equipment, that includes the telephone set, as shown in Figure 1-3. The telephone set is also called an "instrument." We'll often refer to the telephone set as the "telset" for short.

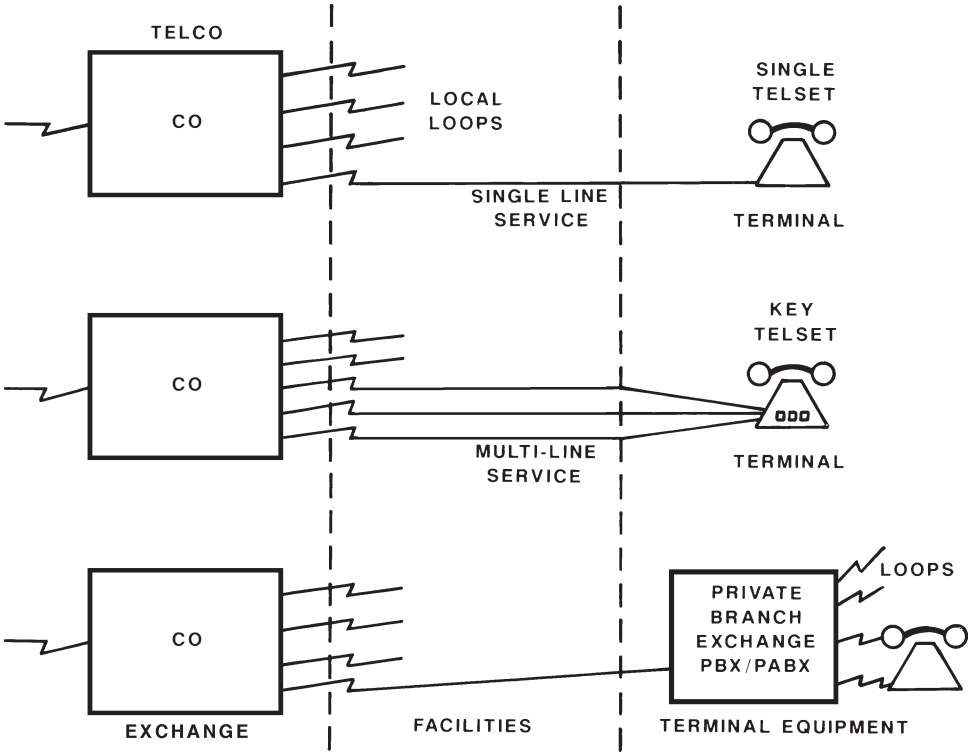


Figure 1-3
Local telephone service.

> The telephone set is called a "telset." It is an "instrument" classified as "terminal equipment."

The most common facilities for voice telephone service is the two-wire circuit, wired telephone line, that connects to a simple single line telephone. This telephone line is also called a "wire-pair," "twisted pair," or "cable pair." The telephone in your home is most likely a single-line telephone. By contrast, telsets in some businesses often operate with multiple two-wire circuits, multiple lines, with push-buttons to select which lines to activate. These push-buttons are called "keys," and the telsets are aptly called "key telephones."

Both the single-line and key telephone systems operate within the larger network that allows them to be interconnected through dial-up switching. This service is called the Direct Distance Dialing network, abbreviated DDD. In the jargon of telephone practice, the DDD service is often called a "dial-up network" or "switched network." With current business practices, a number of independent telephone companies share services and access to the DDD. These many companies provide a large number of the service routes necessary to handle heavy levels of traffic.

Even though telcos are a part of the PTN, they also provide non-DDD *dedicated,* or *switched,* private line services to subscribing customers. Such services are also available from independent telephone and communication companies. Private lines are used for communication by larger businesses and government agencies that must maintain circuits for exclusive use. Fixed point-to-point private lines and circuits provided by telco are also used for non-telephone services such as the studio-to-transmitter links of radio stations.

With DDD service, the telephone messages are routed through a switch at the central office for a local call, through a switching center for an area call, and through the DDD network for long distance call. The area served by a central office and its switches is called a "local exchange." The lines between a central office and subscriber are called a "local loop." Figure 1-4A diagrams this DDD service. With private services, the process is identical, but much smaller in scale. The smaller equivalent of the central office and switch is called a "private branch exchange," abbreviated PBX. (PABX and EPRBX are automatic and electronic equivalents of the PBX.) Depending upon a company's service needs, the output of the PBX may access the PTN and/or private network circuits. Figure 1-4B diagrams the PBX.

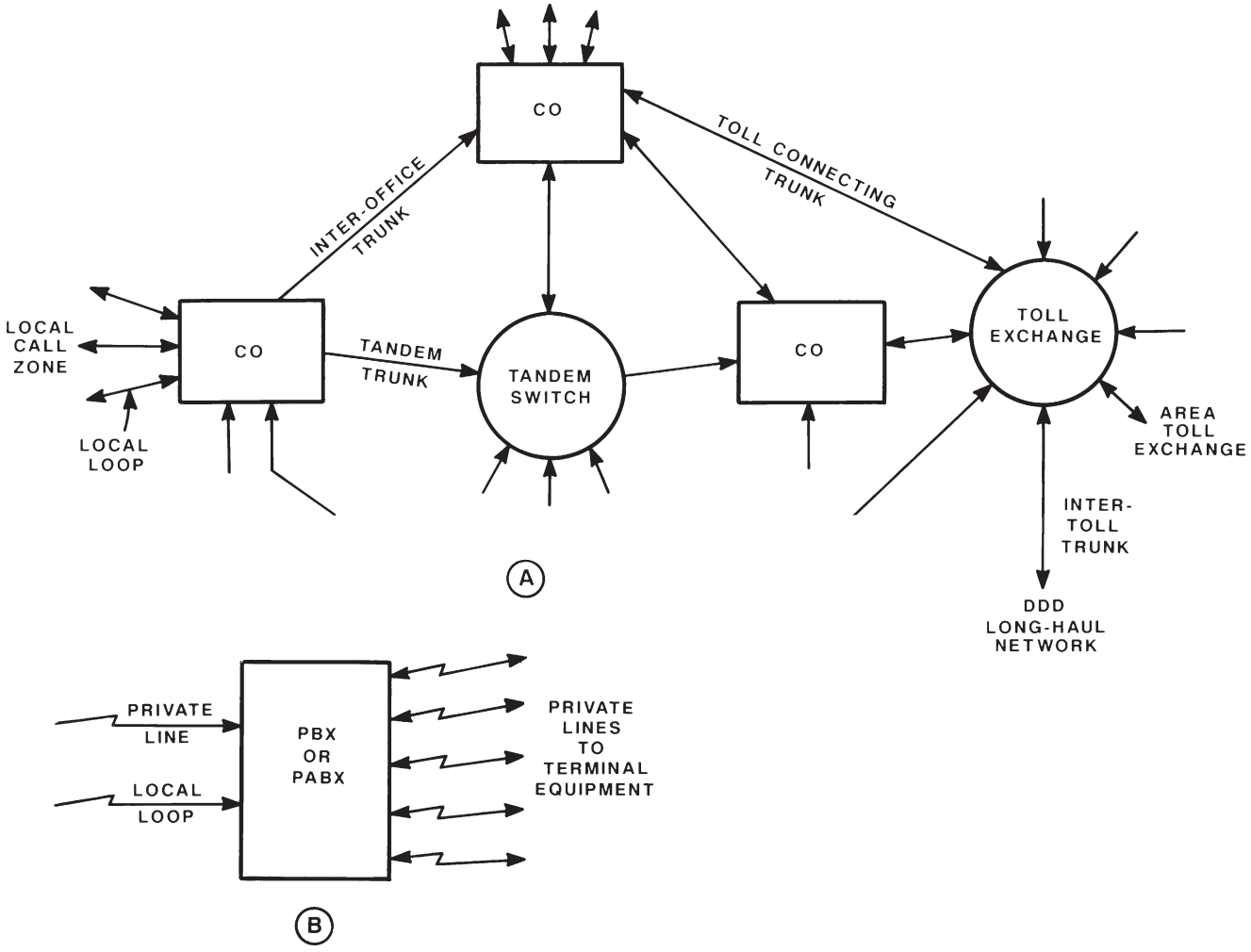


Figure 1-4

Telephone exchanges.

THE LOCAL LOOP

The term "local loop" is used to identify the pair of wires and connections between the central office and the telset. Each subscriber is connected to the central office through the local loop. The two-wire line of the local loop has each of its wires identified by the way they were connected to standard phone plugs in early manual telephone switchboards. One wire connects to the center contact on the plug at its tip. This wire is called the "tip wire," "tip connection," or "tip terminal." The second wire connects to the barrel ring contact of the phone plug. It is called the "ring wire," "ring connection," or "ring terminal." The sleeve of the phone plug is used for a third wire or a ground connection if required.

In the line to the telset, the terminals are identified by the color of the wire insulation. The tip wire is insulated green in color, and the ring wire is red. Figure 1-5 shows the tip and ring wires of the local loop, along with the general circuits of the central office and telset.

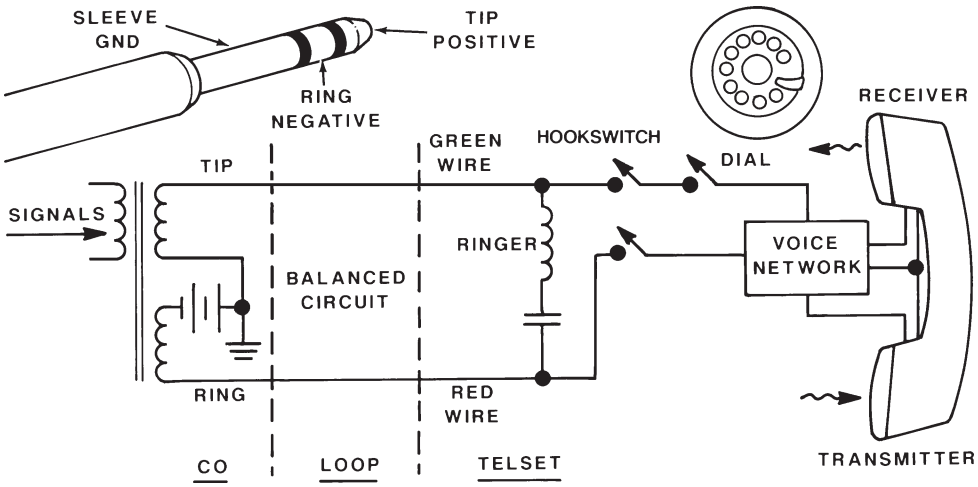


Figure 1-5

Circuits of the CO and telset.

The local loop is the two-wire circuit between the central office and the telset. One wire is the tip terminal, and the other wire is the ring terminal.

In addition to providing a wire circuit path for voice information, the central office furnishes power to operate the telset at the subscriber end of the local loop. In early telephone systems, this power was provided by batteries. The term "talk battery" still remains to describe this source of power from the central office. In most telephone systems, the "talk battery" power source supplies either –24 or –48 VDC. Note that the supply voltage is negative with the positive side of the power source grounded. The ring terminal carries the negative voltage from the power source while the tip terminal carries the positive (grounded) supply voltage.

Even though the central office applies 24 or 48 volts to the local loop, the voltage drops considerably by the time the current reaches the telset. The long lengths of wire from the central office to the subscriber accumulate considerable resistance, which causes large voltage drops. The telephone system accommodates lower voltages, however, as it operates on current, not voltage. The typical limits for telset operation range from 20 mA to 80 mA DC; and, the telset still operates with as little as 12 VDC remaining across its terminals.

The local loop is a balanced circuit. This balanced circuit is a two-wire line with both of its wires "hot," or above ground, and capable of carrying a signal. By contrast, unbalanced circuits have one of the wires in the line pair grounded, with the other wire serving as a "hot" signal lead. The local loop is grounded through a center-tap transformer at the central office, with one side of the center tap connected in series with the talk-battery power source, as shown in Figure 1-5. The tip terminal of the line carries the grounded positive side of the power source, but the terminal is not directly grounded. It is "hot," or raised above ground, for voice and other AC signals, through its central office transformer connection, and there is also loop resistance to the central office ground connection from the wire pair.

SIGNALS AND SIGNALING

Many signals are used by telco as distinct communication messages which are needed to operate the DDD system. These signals take the form of simple indications of DC current or voltage polarity, single, dual, or multiple tones at different frequencies, and/or pulses and digital codes. In addition to the actual messages transmitted along the PTN, these signals are required to control switching and other parts of the system, and to provide data necessary for billing business requirements.

Signals in the form of DC, single or multiple frequencies, or pulses and codes, are used by telco define and control its operation.

Telco identifies the signals which are used to connect a call through a switch as "address signals." The dial pulses or tones are address signals. They end up at a place, an address, in the switch. The signals which inform the caller of a line's condition are called "advisory." A dial tone and busy signal are advisory signals. They advise the caller of circuit or other conditions. The signals which are used for operational and business purposes are "supervisory." The signal that indicates a completed call, when the called party picks up the telephone, is a supervisory signal.

The telset terminal delivers three distinct signals, which are communication messages through the local loop and to the central office. The first is a signaling signal from the "hookswitch." This is the switch that is actuated when you lift the telephone's handset. The two conditions of this switch are "on-hook" and "off-hook." These terms originated from earlier times when the telephone receiver was attached to a real hook that switched when the receiver was lifted. When the handset is in its cradle, or "on-hook," the telset is inactive, the hookswitch is open, and no current flows from the talk battery of the central office. When the handset is lifted from its cradle "off-hook," the telset is active, the hookswitch is closed, and current flows from the central office's talk battery.

The second signaling signal from the telset is the dial pulses or dial tones (frequencies). The dial signal activates the switch at the central office to select the calling number. Dial pulses are the earlier standard of the DDD network while the dial tones are the modern technique of accessing the DDD network. The DDD network accepts and switches dial signals as either pulses or tones. The dial pulses result from sequentially interrupting the current flowing within the local loop. These pulses are sensed and registered by the switch at the central office. The dial tones (not the dial-tone) are a combination of two distinct frequencies for each of the push-button digits. The frequencies are detected, and then registered as an equivalent number by the central office switch.

The audio frequency voice information is the third signal from the telset. The transmission of this voice signal is obviously the purpose of the telephone system, but the voice does not remotely activate or control the system (except through the rare human intervention of a telephone operator). So two of the three signals which originate in the

telset, the hookswitch and the dial, are for operating the system, while only one of those signals, the voice signal, contains the direct in formation intended for communication. The sources of theses signals are depicted in Figure 1-6.

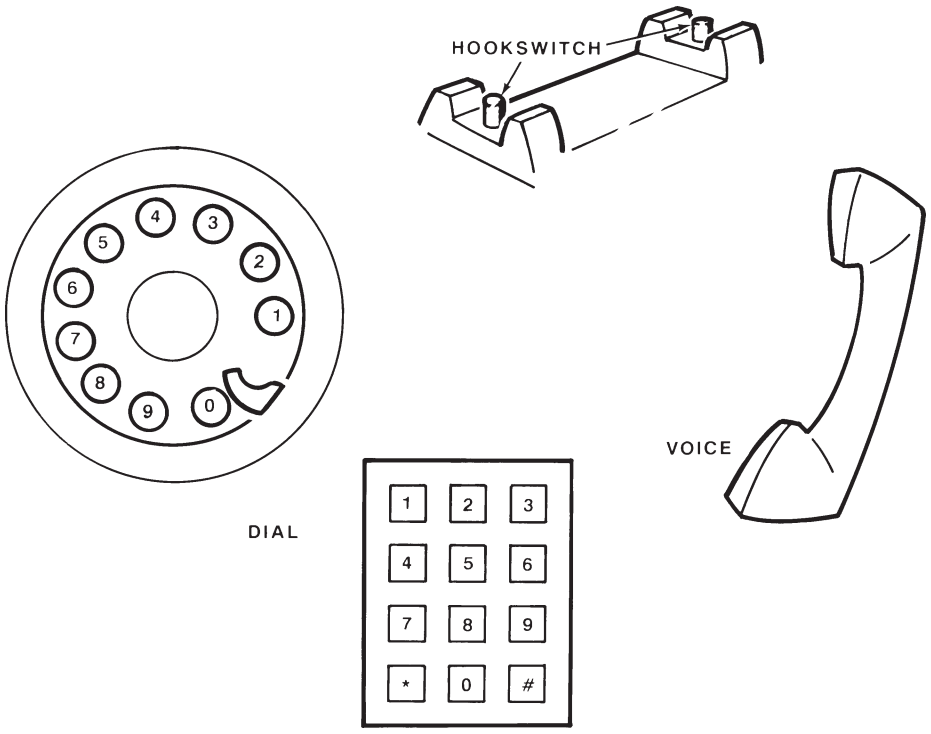


Figure 1-6

Three signals are available from the telset. These are hookswitch, dial, and voice information.

While there are only three signals that originate in the telephone set, there are many signals that originate in the central office. Some of these signals are applied to the local loop and calling party telset at its terminal, while other signals are applied to the operation of the central office, its switch, and the called party served by the central office. Still other signals are applied to the DDD network. Since the overall telephone system is extensive, control of this system is quite complicated. Remember that any telset attached to the PTN can be connected to any other of the billions of telsets served by the PTN.

Let's proceed first to identify those central office signals that you may hear as tones in your terminal telset. These include the dial tone, the ringer and ring-back signals, the busy signal, and the loud receiver off-hook signal or recording. There are also less-often heard signals applied by the central office, including a circuit congestion tone, and a frequency shifting tone used to indicate "no such number" that the number dialed doesn't exist, or can't be accessed by the central office's switch.

Signals detected by the central office, but not by the subscriber, include those classified as "DC signaling." The initial signal received by the central office is the DC current flow when the telset goes off hook. This DC signal activates the central office to apply dial tone to the local loop. Another form of DC signaling, called "E & M signaling," is used between one central office switch and another, not in the local loop. The letters E & M are used to designate specific wire lines in two-way circuits between central offices. The abbreviations originated in early telephone practice as "ear" (E) and "mouth" (M) to identify the talker and listener connections. The presence and polarity of the DC voltage on these lines is used to advise the originating central office of the called central office's hook status, on-hook or off hook. DC signaling signals are also often superimposed upon voice and tone signals in two-way circuits that don't have E & M wires. These DC signals are then identified as "DX (distance) signaling," as shown in Table 1-1.

Table 1-1

Telephone signals.

SIGNAL	PURPOSE	CHARACTER
Hookswitch	Request for Service	Activated
Dial	Access to Switch	by Caller
Voice	Communication Message	
Dial Tone	Indicates Line Seized	Detected by
Ringer	Advises Called Party	Caller and
Ringback	Advises Caller	Called Parties
Busy	Advises Caller	
Receiver off Hook	Advises Caller	
Circuit Congestion	Advises Caller	
No Such Number	Advises Caller	
Loop DC	Request for Service	Not Heard by
E & M	Line Use Between Exchanges	Caller or
DX	Line Use Toll Exchanges	Called
SF	Toll Line Available	Parties
Misc.	Communication Between CO's and/or Other Exchanges	

There are, yet, other signals tone signals which are detected by the central office, but not by the subscriber. These include single, dual, and multi-frequency tones used by telco for their operations. The SF (single-frequency) signal is a 2600 Hz tone that is present on unoccupied lines and circuits. The signal is disabled when the lines or circuits are occupied, so it is not heard by the subscriber. Multifrequency and data signals are also sent along the circuit beyond the central office, not on the local loop, along unoccupied lines.

The frequencies of these signals are in-band, within the bandpass of the 3 kHz frequency response of the telset. The bandpass of the voice channel, within the telephone system, is DC to 4 kHz, while the bandpass for voice information is 300 Hz to 3 kHz. The portions of the channel bandpass not available for voice signals are said to be "out-of-band." The out-of-band frequencies can be used for tone signals on occupied lines. Again, these are not heard by the subscriber. Figure 1-7 diagrams the in-band and out-of-band signals.

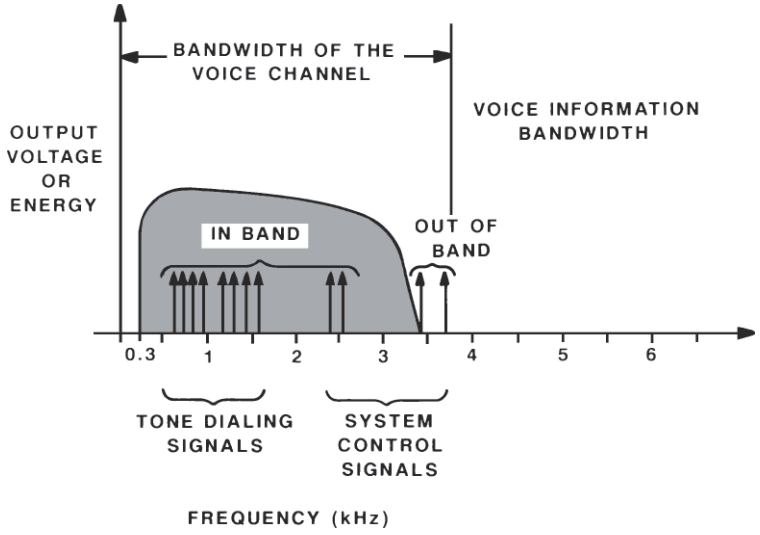


Figure 1-7

In-band and out-of-band signals.

SEQUENCE OF OPERATION

A useful way to understand telephone service is to follow the sequence of its operation in completing a phone call. We will first review the simplest of connections, a local call with both caller and called parties served by the same central office. Later, we will follow the path of a call through other central office's, as well as through other exchanges within the DDD network. As you read through this section, we recommend that you actually use your telephone to investigate, and affirm, the operating conditions described.

Completing a Local Call

1. To originate a phone call, the handset is lifted from its cradle, which puts the telset in the off-hook condition. When the switch goes off-hook, it completes the circuit path of the local loop, which allows current to flow through the circuit. This step is called a "request for service." The DC loop current signals the central office to apply a dial tone to the circuit.

2. The DC loop current also starts a timer which limits access to the switching center. This timer is called a "time-out circuit." If dialing doesn't begin within a preset period, typically 15-to-30 seconds, the loop is disconnected from the switch access, and a reorder signal, or a recorded message is applied to the local loop from the central office. The message instructs the caller to "hang up and dial again." The central office switch is shared equipment, so access time must be limited for its optimum availability. The local loop is also shared, and its optimum use directly affects telco's revenue, so the switch circuits are designed for minimum tie-up time with any local loop.

3. If dialing is started before the limit of the time-out circuit, each dial digit, a pulse sequence or tone frequency pair, is stored in the central office switch. If the sequence of digits is not dialed within a preset period, again typically 15-to-30 seconds, another recorded message is applied to the local loop from the central office's switch. The message advises the caller that the "call cannot be completed as dialed," and to "hang up and dial again." The same message is applied to the local loop for most examples of incorrect dialing. This is shown in Figure 1-8.

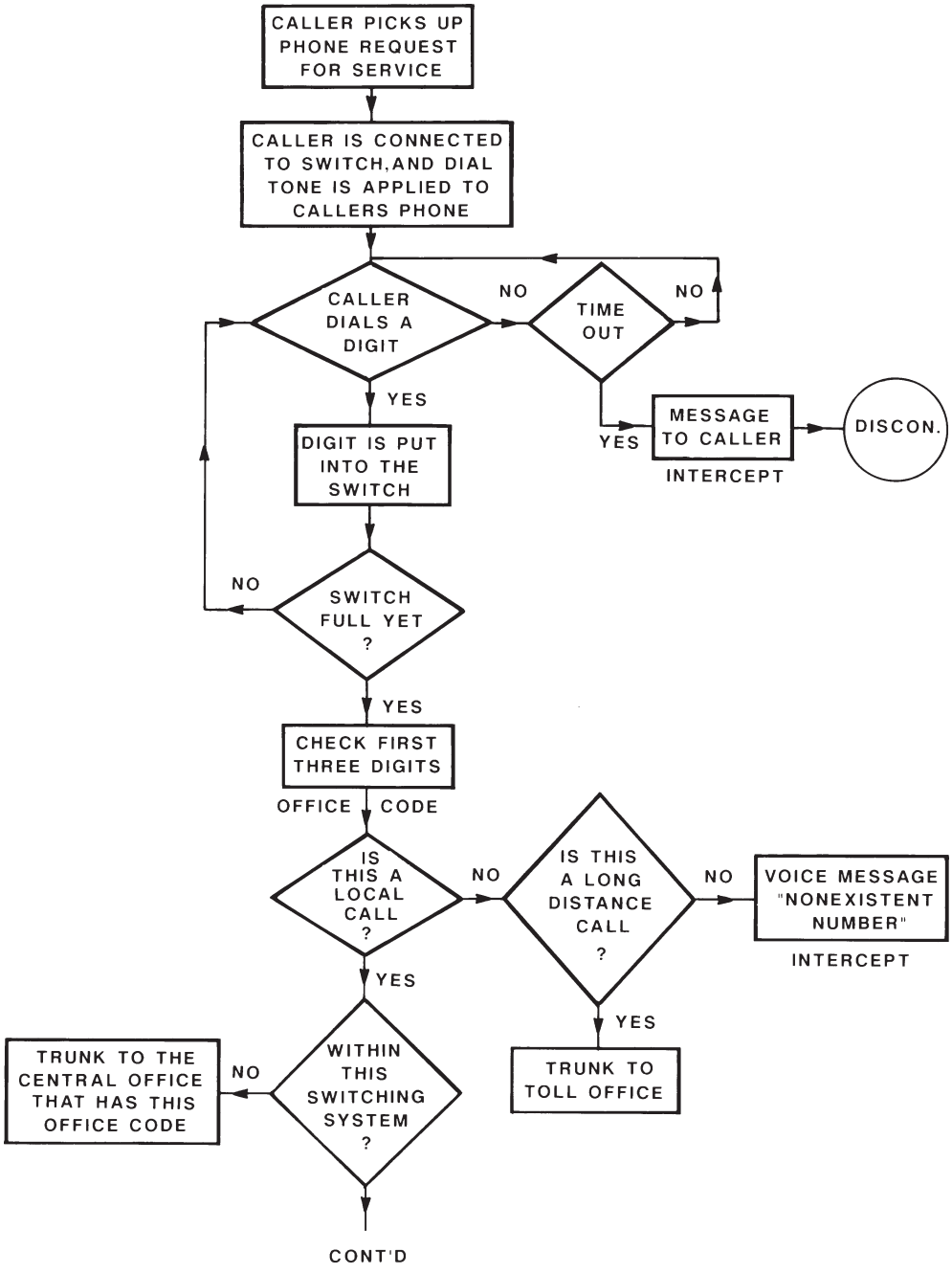

CALLER PICKS UP PHONE REQUEST FOR SERVICE
CALLER IS CONNECTED TO SWITCH, AND DIAL TONE IS APPLIED TO CALLERS PHONE
CALLER DIALS A DIGIT
NO
TIME OUT
NO
YES
MESSAGE TO CALLER
DISCON.
INTERCEPT
YES
DIGIT IS PUT INTO THE SWITCH
NO
SWITCH FULL YET ?
YES
CHECK FIRST THREE DIGITS
OFFICE CODE
IS THIS A LOCAL CALL ?
NO
IS THIS A LONG DISTANCE CALL ?
NO
VOICE MESSAGE "NONEXISTENT NUMBER"
INTERCEPT
YES
YES
TRUNK TO TOLL OFFICE
WITHIN THIS SWITCHING SYSTEM ?
NO
TRUNK TO THE CENTRAL OFFICE THAT HAS THIS OFFICE CODE
CONT'D

Figure 1-8

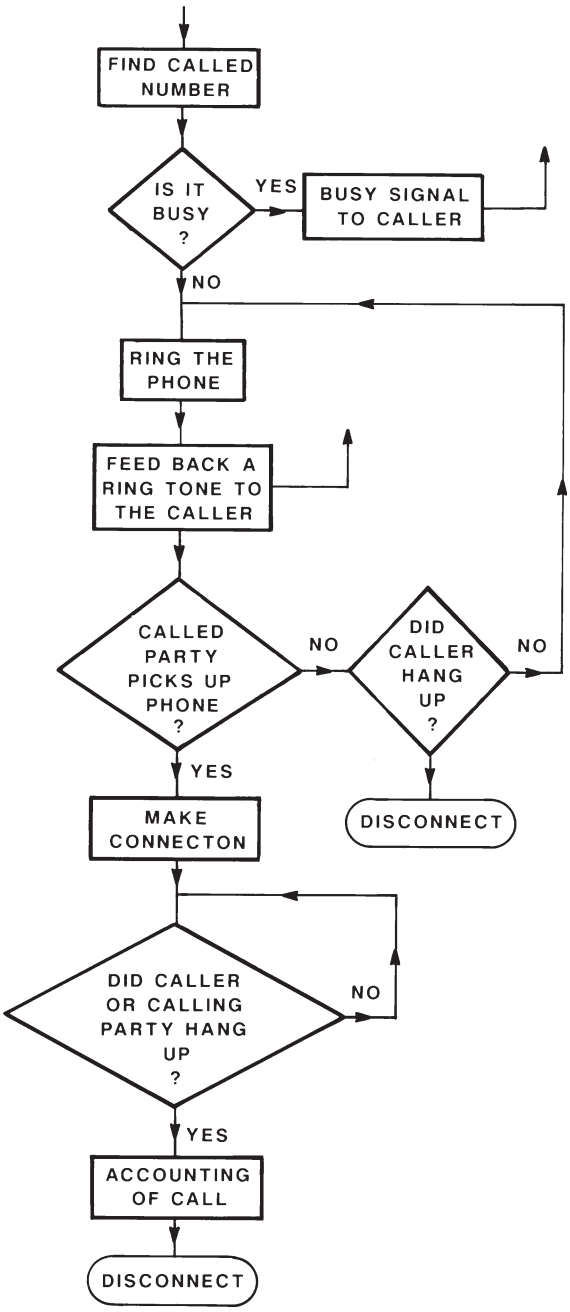

FIND CALLED NUMBER
IS IT BUSY ?
YES
BUSY SIGNAL TO CALLER
NO
RING THE PHONE
FEED BACK A RING TONE TO THE CALLER
CALLED PARTY PICKS UP PHONE ?
NO
DID CALLER HANG UP ?
NO
YES
MAKE CONNECTON
DISCONNECT
DID CALLER OR CALLING PARTY HANG UP ?
NO
YES
ACCOUNTING OF CALL
DISCONNECT

Figure 1-9

4. Once the dialing sequence is correctly completed, the central office switch transfers the dial data in its registers to a circuit called "processor control" which frees the switch circuits for access by other callers. The called number now resides in a switch location called a "dial address." For a local call, the call processor portion of the switch now scans the lines of the central office to access the local loop of the called subscriber. If the DC signal on the subscriber's loop indicates an off-hook condition, a busy signal message is returned to the caller's local loop.

5. If the called party's telset is on-hook, the central office activates a high-voltage ringer signal on the called party's local loop, and then activates a low-level ring-back signal on the caller's local loop. (The ring-back signal is created from a generator independent of the ringer signal.) Both ring generators are disconnected by the DC signal that results when the called party goes off-hook by lifting the handset from its cradle. This same DC signal connects the voice circuits of the calling and called parties, and activates an accounting circuit to time the call for billing, as shown in Figure 1-9.

6. At the completion of the phone call, both the calling and called parties go on-hook, which stops the accounting timer, causes a disconnect between their voice circuits, and restores both local loops to their initial on-hook status with the central office.

CALLING BEYOND THE LOCAL CENTRAL OFFICE

The process of completing a call beyond the local central office begins the same as a local call, proceeding through Step 3 of the previously outlined sequence. At this point, however, the circuit paths through the network become complicated. When a call must be made from the central office in one area, to a central office in another area, for example, many alternate switching and circuit routes are scanned to obtain a line that is not in use. Sometimes, a circuit path hundreds of miles long must be selected to complete a telephone call to two points only 30 miles apart. Such circuit routing becomes an especially difficult problem during periods of heavy telephone traffic.

Circuit routing complicates the process of telephone communication beyond the local central office.

The details of call routing are complicated, as the process depends upon variables beyond the scope of this text. The processes are sufficiently complicated to require a specialized discipline called "traffic engineering." In this text, we will describe only the generalities of connecting telephone calls, and identify a "connection" as the route through which the call is passed from telset to telset.

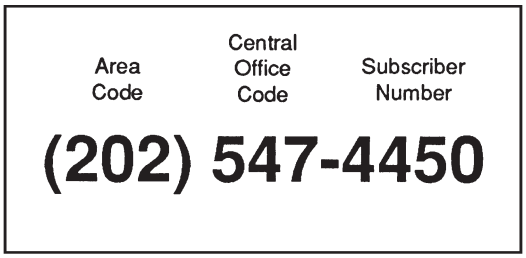


Figure 1-10

To study the generalities of the routing process requires your knowledge of telco's digit dial numbering plan and service coverage. As shown in Figure 1-10, the first three digits of a ten-digit telephone number access the area switch, the second three digits access the central office for a specific zone, and the last four digits access the local loop connection to a subscriber. With four digits available, the maximum number of subscribers-per-central office is 10,000 (0000 to 9999). With three digits available, the maximum number of central offices and areas are 1000 each (000 to 999). In practice, these numbers are not used to capacity in order to accommodate growth and changes in service.

Each central office serves local subscribers, and use the last four digits of the telephone number. Many central offices cover a zone of service within an area, and use the next three digits of the telephone number. The first three digits of the telephone number cover each area of service.

The additional central offices in a locale may be located in the same building, but more often in separate buildings throughout a zone, with circuit connections between each of them. The circuits, or wire paths between these local central offices are called "trunks" or "trunk lines." There are direct connections between each of the central offices, called "interoffice trunks."

To access the other central offices with interoffice trunks requires information to pass through each central office in a series path. To increase efficiency and capacity, an additional switch is employed to connect central offices in a manner similar to the way that central office's access local loops. This switch is called a "tandem switch." The tandem switch connects many central offices through tandem trunk lines. Figure 1-11 shows the generalized connections of the central office and tandem switches.

Calls out of the primary area served by tandem-switched central offices, pass through another level of switching that selects available circuits and transmission media for long distance communication. This level of switching and circuits is called the " long-haul network." The switch that accesses the long-haul network is called the "toll center." The trunks into the toll center are toll-connecting trunks, while the trunks out of the toll center are inter-toll trunks.

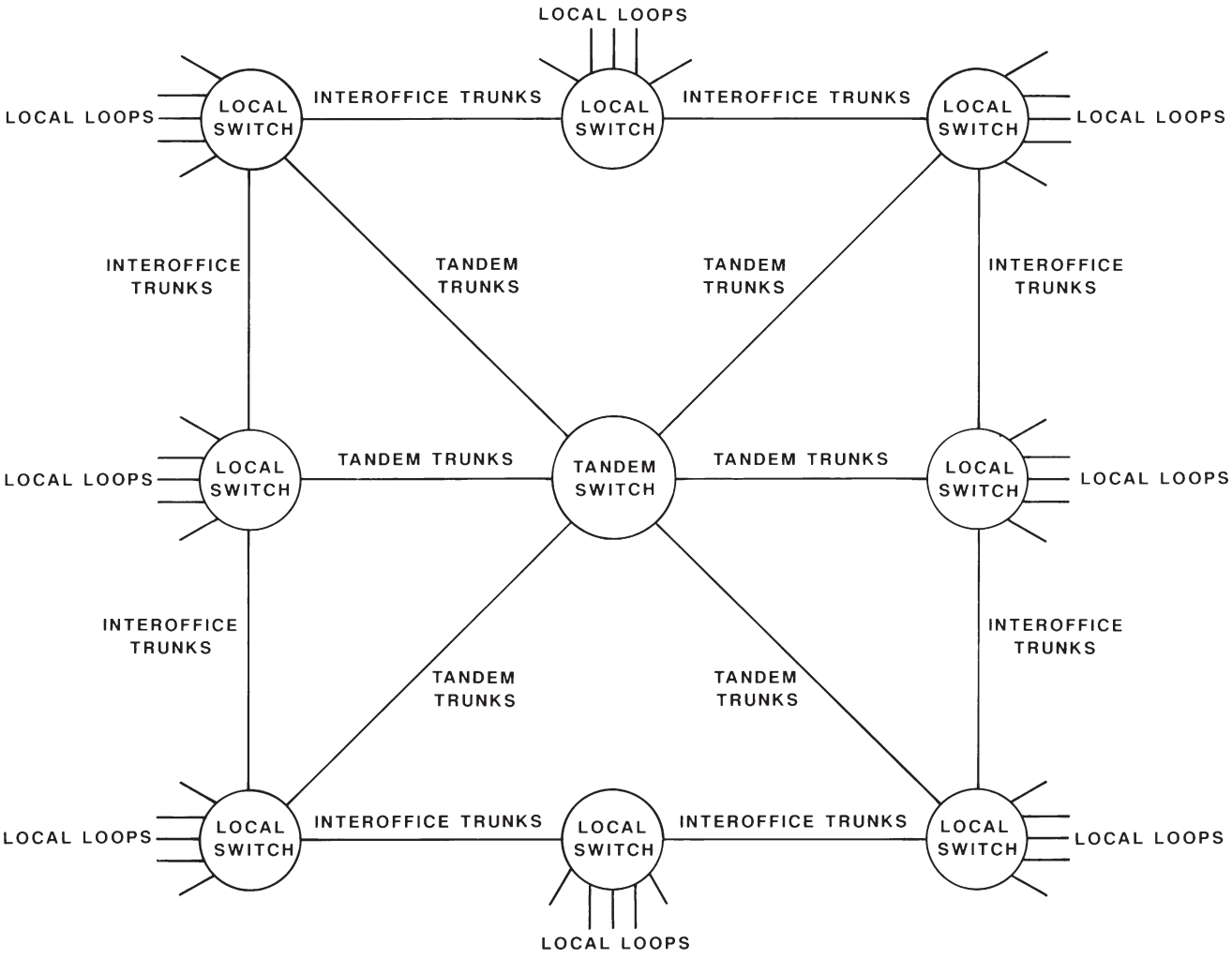


Figure 1-11

Connection of CO and tandem switches.

To transfer phone calls and other information, the long haul network uses many types of transmission media in addition to wire circuits. Other common types of transmission circuits include cable, radio, microwave, satellite, infra-red, and fiber-optic links. This network is complicated by the standards for each distinct transmission medium, and the techniques used to operate its circuits and systems. Each time traffic passes from one type of media to another, different operating standards must be used to access the other medium.

As mentioned earlier, access to, and through, the DDD network is very complicated due to the number of possible circuit paths that must be available to handle large amounts of traffic. To get beyond the local central office, the PTN has evolved a switching hierarchy for toll circuits. This hierarchy specifies classes of switches and switching centers for selecting routes and completing circuit paths.

Figure 1-12 shows a switching hierarchy of the toll circuits typically used by AT&T. The local loop and tandem switches which are used in central office's are specified as Class 5. The Class 5 switches are located at an end office of the DDD network. The switches at the toll centers are specified as Class 4. Beyond the toll centers, there are yet higher capacity switches that connect routes. The AT&T hierarchy is primary centers with Class 3 switches, sectional centers with Class 2 switches, and regional centers with Class 1 switches. The capacity of switches and circuits is greater within the lower-numbered switching centers. The structure and switching hierarchy of long-haul companies other than AT&T vary greatly.

With the large number of circuit paths required for switching, and a variety of media used for transmission, standards must be maintained throughout the DDD network to assure quality service. The quality of service is improving through computer-controlled electronic switching systems (ESS) in the DDD network. These systems scan and select an available transmission path that provides the quickest connection. The circuit may not necessarily be the shortest, or most direct, transmission path between switching centers.

As you proceed with your study of the telephone and its circuits, you will appreciate its simplicity. The successful operation of the local loop telephone uses simple technology that is over 100 years old. However, adding the complexity of selecting quality circuit paths to an already complicated large DDD network of switches, is what makes telecommunication technology one of the most sophisticated modern electronic systems evolved by mankind.

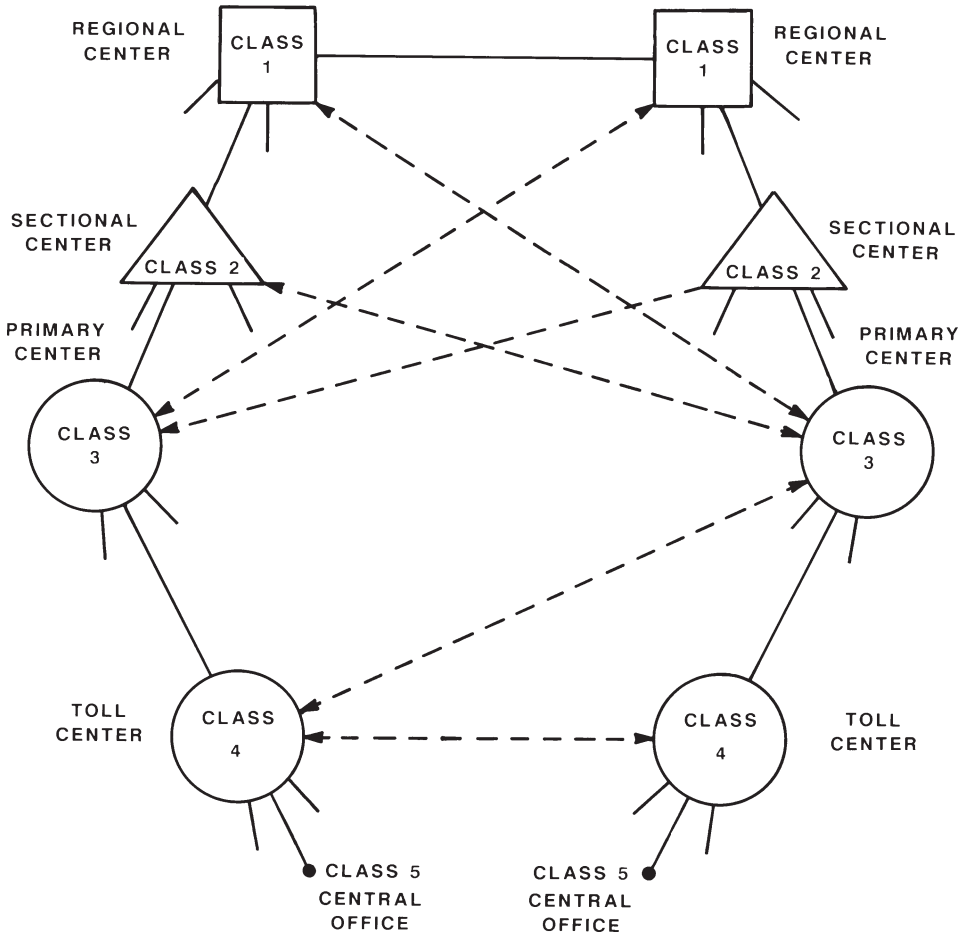


Figure 5-12

AT&T long-haul switching hierarchy.

SUMMARY

In this chapter, we described the operation of local telephone services. We first introduced the structure of the Public Telephone Network **(PTN)**, and its access to the world-wide installed base of telephones. In describing the PTN, we also introduced the distinctive terminology, acronyms, abbreviations, and codes used in communication practice. The major value of the PTN was described as its access by any telephone, to the millions of other telephones throughout world.

The focus of the first four chapters of this Course is local, single-line telephone service. A thorough understanding of this service is fundamental to all aspects of telecommunications. Single-line telephones are served by a central office (central office), which provides power to the telset and access to the PTN. A major section of the central office is its switch. The switch connects incoming lines and outgoing lines within its area of service, and it provides access to other switches throughout the PTN.

The central office serves its subscribers through wire cables. The cables begin with over 1000 wire pairs, which are then divided into smaller groups of wires for final distribution to the telsets. The wires are terminated in intermediate junction boxes, where they are connected to smaller 4-wire cables for connection to the residence or business using single-line services. The wires, junction boxes, and connection points for service from the central office are called "facilities."

The wires that terminate at the telset are identified by their color, red, and green, and by how they were used by early telephone operator's patch cords. These cords were connected to phone plugs that identified their wires as "ring" and "tip." The red ring lead is negative, while the grounded green tip lead is positive. The wires carry current from the central office for the telset's operation. The conventional electrical telset operates on current, not voltage.

SELF-TEST REVIEW

1. Which is the primary factor that allows the PTN world-wide access?

   A. Satellite Networks.
   B. Electronic Switching Systems.
   C. Network Compatibility.
   D. Digital Signal Processing.

2. Which component is **NOT** a part of the single-line telephone set?

   A. Transmitter.
   B. Talk battery.
   C. Voice network.
   D. Hookswitch.

3. Which of the following does **NOT** originate from the central office?

   A. Dial tone.
   B. Ringback tone.
   C. Talk battery.
   D. Dial pulses.

4. Which of the following is **NOT** a correct classification for a telephone set?

   A. Facilities.
   B. Terminal equipment.
   C. Instrument.
   D. Telset.

5. Which of the following is **NOT** a correct classification for a telephone line?

   A. Wire pair.
   B. Network pair.
   C. Twisted pair.
   D. Cable pair.

6. Which is correct for one wire of the telephone line?

   A. Tip, red, negative.
   B. Ring, red, negative.
   C. Ring, red, positive.
   D. Tip, red, positive.

7. Under which voltage or current conditions will the telephone set **NOT** properly operate?

   A. 15 V, 10 mA.
   B. 30 V, 20 mA.
   C. 45 V, 40 mA.
   D. 60 V, 80mA.

8. Which transformer connection shown in Figure 1-13 provides a "balanced" output?

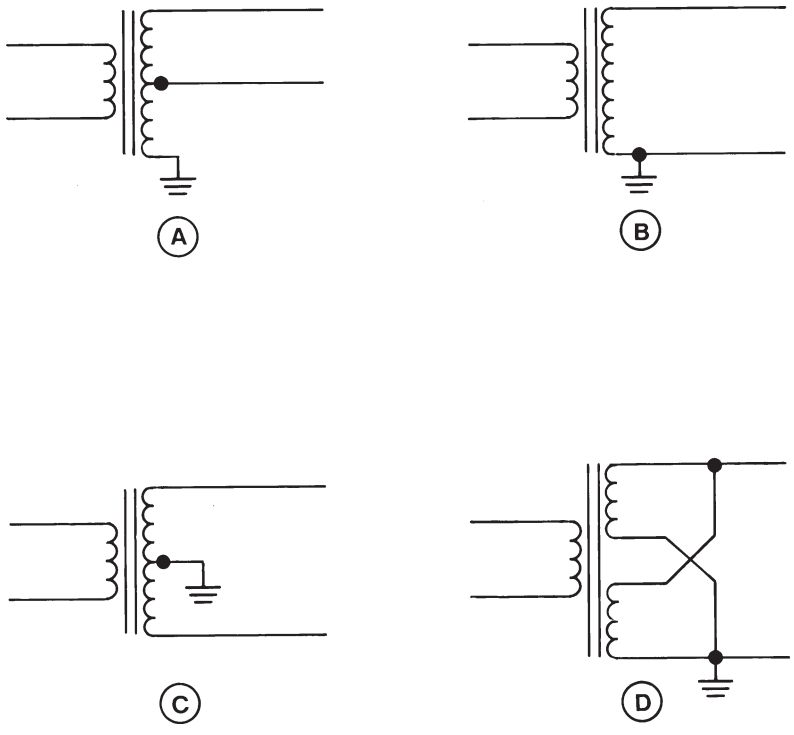


Figure 1-13

Four transformer connection diagrams: A, B, C, D.

9. Which type of signaling signal informs the caller that the dialed line is busy?

   A. Voice signal.
   B. Address signal.
   C. Advisory signal.
   D. Supervisory signal.

10. Which type of signaling signal provides data on calls for billing telco's customers?

    A. Voice signal.
    B. Address signal.
    C. Advisory signal.
    D. Supervisory signal.

11. Which condition is correct, and allows direct current to flow through the telephone set?

    A. On-hook, closed hookswitch.
    B. Off-hook, closed hookswitch.
    C. On-hook, open hookswitch.
    D. Off-hook, open hookswitch.

12. Which of the following frequencies are out-of-band?

    A. 800 Hz.
    B. 1800 Hz.
    C. 2800 Hz.
    D. 3800 Hz.

13. List the sequence of correctly completing a local call to a line that is Not busy.

    1. _____
    2. _____
    3. _____
    4. _____
    5. _____
    6. _____

14. Identify the exchanges accessed by the following:

    A. Last four digits of the dialing numbering plan.
    _____

    B. First three digits of the dialing numbering plan.
    _____

    C. Second three digits of the dialing numbering plan.
    _____

15. What is the maximum capacity of local loop numbers available from a single central office?
    _____

16. In identifying telephone lines from a central office, what is the difference between a "loop" and a "trunk?" _____
    _____

    _____

17. What is the name of the switching center that accesses the "long-haul network?" _____

18. List the switching hierarchy for the long-haul network, including the class of switch, the name of the office center, and the name of the trunks connecting the centers.

    _____
    _____
    _____
    _____
    _____

CHAPTER 2 — Telephone Equipment

INTRODUCTION

In the terminology of telecommunications, the telephone set is called a "telset," and it is an instrument classified as terminal equipment. Terminal equipment is what connects to the end, the terminal, of a circuit. Terminal equipment, such as the telset and its wires form a station. Each station connects to the central office through a junction box, and the wiring facilities of the local loop. A PBX (a business exchange) is also considered station equipment. Figure 2-1 shows the terminology applied to the connections between the telset and the central office. This chapter describes the various parts that make up a telset.

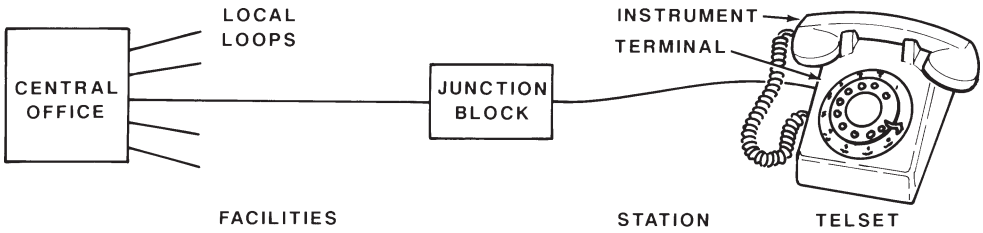


Figure 2-1
CO/telset connection.

OBJECTIVES

When you complete this chapter, you will be able to:

- Identify the name, function, and operation of each of the functional parts of a telset, central office, and local facilities.
- Specify the operating voltages, currents, and frequencies of the central office and telset required for proper operation of local telephone services.
- Specify the wiring connections between the local central office and telset for proper operation of the telephone services.
- Describe, in detail, the operation of a transformer and electronic hybrid voice network, as used in the telset.
- Specify the time standards for dial pulses used to access locations in the central office switch and complete a telephone circuit.
- Specify the frequency and time signals for Dual Tones Multi-Frequency (DTMF) to access locations in the central office switch and complete a telephone circuit.
- Describe the detailed operation and function of each component in the electronic single-line telset.
- Describe the functional operation of each section of the electronic single-line telset.

THE TELEPHONE SET

Figure 2-2A shows the external parts of the single-line telephone set. The telset is comprised of many parts. Its handset contains an earpiece, or receiver, and a mouthpiece, or transmitter. The handset fits on the cradle of the telset's housing. The hookswitch is part of the cradle assembly. The rotary or tone-pad dial are on the faceplate on the telset's housing. Figure 2-2B shows similar parts of a key telephone, with the addition of key switches on the faceplate.

> The main external parts of the telephone set include the handset, cradle, housing, and dial.

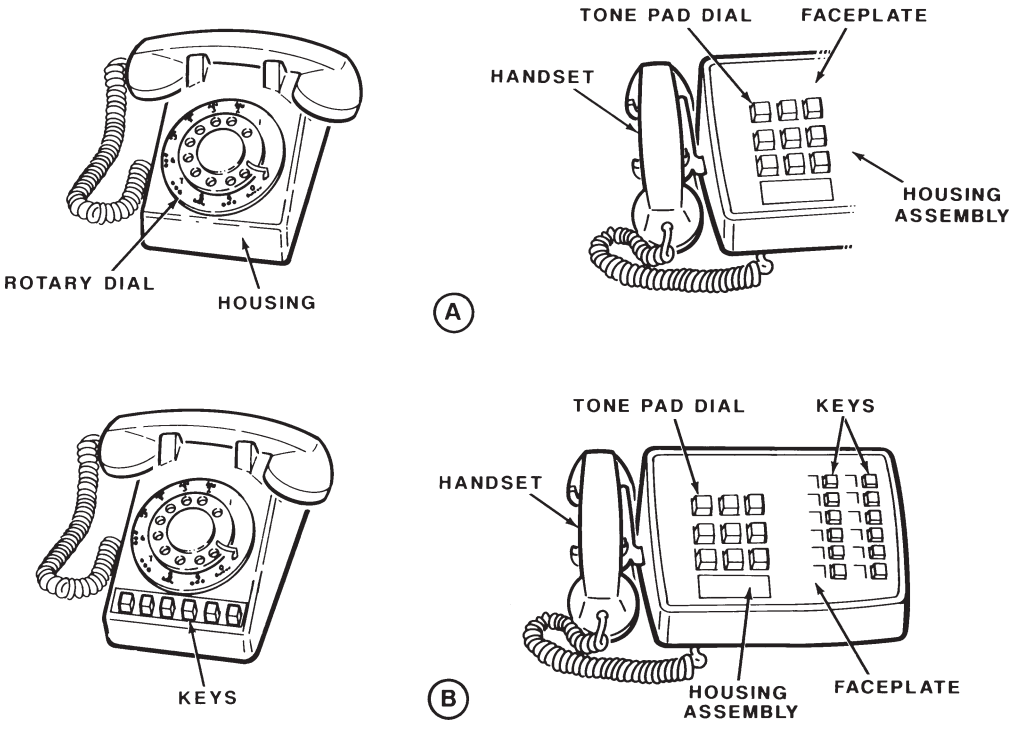


Figure 2-2
External parts of telset.

Figure 2-3 shows the circuits and components within the single line telset. The handset contains the speech input transmitter transducer, and the sound output receiver transducer. The transducers connect to a voice network assembly, which connects through the dial network (pulse or tone dialing), and the hookswitch, to the telephone line. The ringer assembly is always connected across the telephone line.

> The electrical parts of the telephone set include the transmitter, receiver, voice network, dial network, hookswitch, and ringer.

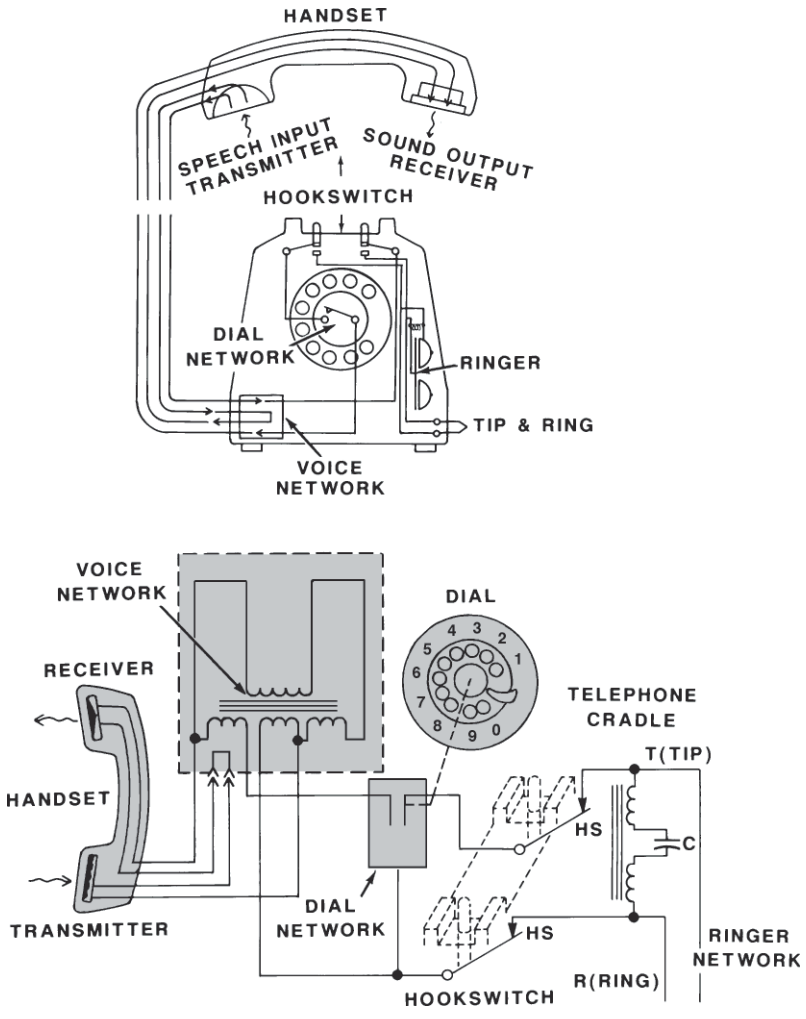


Figure 2-3
Telset circuits and components.

While all small electrical circuits may be referred to as networks, when the word "network" is used alone, it always refers to the speech network circuit within the telset. This network connects the transducers in the handset to the incoming line through the hookswitch. References are also made to other networks, such as the LC circuit of the ringer. In these cases, the word network is almost always used with a word that identifies it, e.g. the "ringer network."

The telset operates best within the range of 20 to 80 milliamps DC from the central office. The ring (negative supply voltage) is the red wire; while the tip (positive/grounded supply voltage) is the green wire. The negative supply voltage, the "talk battery", is usually –48 VDC at the central office. However, this voltage will drop, due to the resistance of the length of wire from the central office to the telset. The typical range resistance of the local loop is from about 100 ohms to about 1600 ohms. The typical DC resistance of the telset is about 200 ohms. Remember, the telset is a non-critical current operated device, so a specific or regulated voltage source is not required for its operation.

In operation, direct current from the central office will flow in the local loop only when the handset is off-hook. Referring to Figure 2-3, you should observe that the hookswitch completes the DC path through the network that loads the line from the central office. Although the ringer is always connected across the line, direct current will not flow through it due to the blocking capacitor in the ringer network.

Electrically, the words "load" and "termination" are similar. The load on a circuit determines the current flow in proportion to the voltage at its terminals. The termination of a circuit is that element that is at the end of a circuit. In the telset, the line from the central office terminates at the network, and the network impedance is the load impedance of the telset. With the telset on-hook, the DC line path is terminated in an open circuit, and the AC line path is terminated in the ringer network's impedance.

The ring signal is a high-voltage AC signal, which can be applied to the local loop only when the handset is on-hook, and when no direct current flows on the line. The ringer network is a simple LC circuit that is resonant in the range of 20 to 30 Hz, the frequency of the ring signal. In non-electronic telephones, the inductance of the ringer network also serves as the electromagnet solenoid for the bell clapper. In electronic telephones the ringer network may be a solid-state frequency detector, which drives a buzzer or other annunciator transducer.

The typical voltage of the ringing signal is about 90 volts rms at the central office. This voltage level will be lower at the telset, due to the resistance of the wire in the local loop. The ringers on most telsets will properly operate with voltages as low as 50 volts rms.

THE NETWORK

The network in the telset, sometimes called a "voice network" or a "speech network", is a distinctive arrangement of transformer windings, or an electronic integrated circuit, that takes advantage of the effects of phase. The network provides for the sending and receiving of two-way conversation, with messages simultaneously flowing in two directions on the same wire or circuit. This process is called "duplex transmission." The network separates the receive and transmit signals, from the two-wire line, to four wires, with two wires connected to the transmitter in the handset, and two wires connected to the receiver in the handset. Devices that allow for such transmission are called "duplexers." The network is a duplexer.

> The network in the telset operates as a duplexer. It separates transmit and receive voice signals on a single telephone line to and from their corresponding transducers.

Generated voice signals (messages) from the transmitter are connected to one terminal of the network and received voice signals are available at a second terminal of the network. The third terminal of the network connects to the telephone line through the hookswitch, and there is a balance circuit connected to the fourth terminal. The impedance of the network is nominally 600 ohms, to match the telephone line impedance. Figure 2-4A shows the block diagram of the telset network, and Figure 2-4B shows the schematic diagram. Note that the voice network is a complex transformer with many windings.

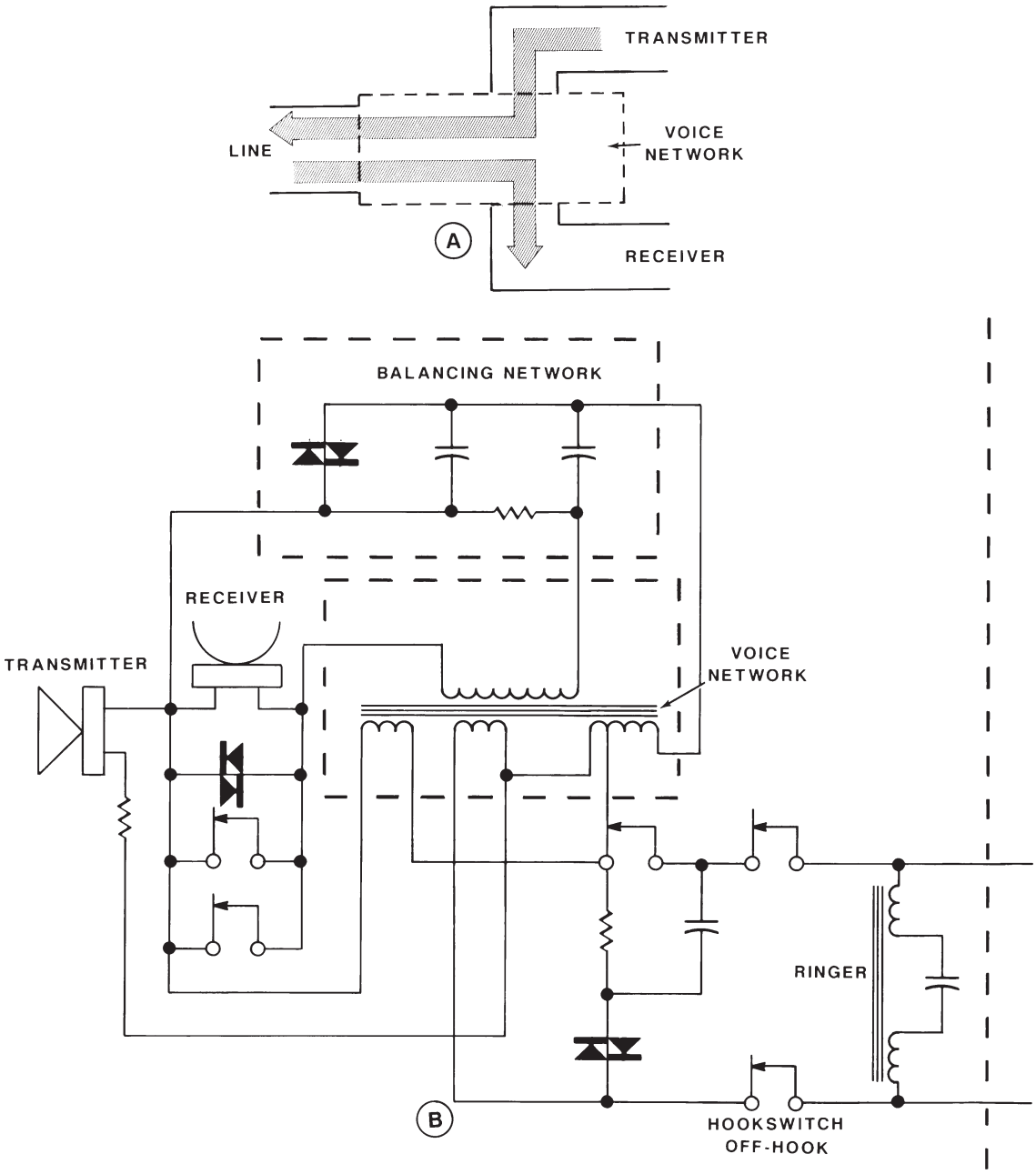


Figure 2-4

Telset voice network.

The Transformer Network

The transformer network is sometimes called a "hybrid," because it is a mixture of separate windings. The network is redrawn in Figure 2-5 in a way that makes it somewhat easier to understand. Referring to Figure 2-5, the transmit signal current passes through winding A of T1, and couples identical currents into the two secondary windings, B and C. These two windings in T1 are wired to two identical windings in T2, D and E. The E winding is connected out-of-phase (for reverse current flow) with winding D. The out-of-phase signals cancel, leaving the transmit voice signal on the telephone line, but not on the receiver terminals.

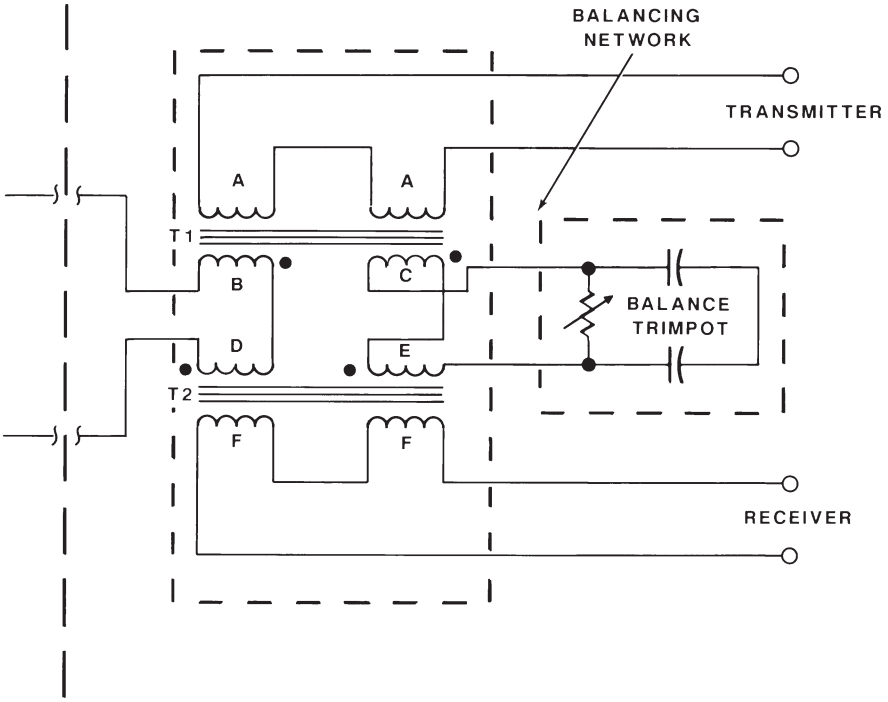


Figure 2-5
Transformer voice network.

One pair of the connected windings, B and D, connect to the telephone line, while the other pair, C and E, connect to a balance potentiometer, or trimpot. The transmit signal applies current to the telephone line from winding B through winding D. The secondary winding of T2, winding F, connects to the handset receiver. With equal currents flowing out-of-phase in both primary windings D and E, their currents cancel each other. The output current on the secondary winding of F are, therefore, zero.

If the balance trimpot is perfectly adjusted to the impedance of the two-wire telephone line output, the level of the out-of-phase currents in windings D and E are identical, and there is a complete cancellation of any transmit signal current at the secondary winding of T2 F. With perfect balance, the transmit signal is not heard in the receiver. In practice, however, the trimpot is adjusted for a slight unbalance, so a very small amount of the transmit voice signal, called the "sidetone," is heard in the receiver. Early in telephone practice, it was determined that callers are more comfortable when they hear their own speech in the receiver of the handset. The sidetone allows the callers to hear themselves, and it gives them an indication of their voice level.

When an incoming receive signal is on the telephone line, it causes a current flow through series-connected windings B and D of T1 and T2. The current in winding C of T1 is out-of-phase, but equal in level, with the current in winding B. The current in winding E of T2 is in phase and equal in level with the current in winding D. With equal currents flowing out-of-phase in both windings B and C of T1, the output current on the secondary winding of T1, transmit winding A, is zero. The incoming voice signal is applied to the receiver, but not to the transmitter. However, with currents flowing in-phase in both windings D and E of T2, the output current on the secondary winding of T2 F is high.

The IC Network

The networks in electronic telephones are typically comprised of IC devices, configured as differential amplifiers. The functions of the electronic networks are identical to those of the transformer types. Incoming voice signals are directed from the telephone line to the receiver, and isolated from the transmitter, while voice signals originating from the transmitter are directed to the telephone line, with only a small sidetone level passed to the receiver.

The incoming and outgoing voice signals are selected through phase cancellation, just as within the transformer. You may recall from your earlier studies that the differential amplifier rejects, phase cancels, common mode signals from its output terminals. The simplified diagram of Figure 2-6 shows the functional circuitry of an electronic network. The transmit voice signal is applied to both inputs of the differential amplifier. This signal is a common-mode signal, so it is canceled, with no voltage difference at the "diff-amp's" output connection to the receiver transducer. The incoming voice signal on the line is applied to only one input of the differential amplifier. This signal is not common to both input terminals, so it is amplified at the "diff-amp's" output connection, with a large voltage difference, and drives the receiver transducer.

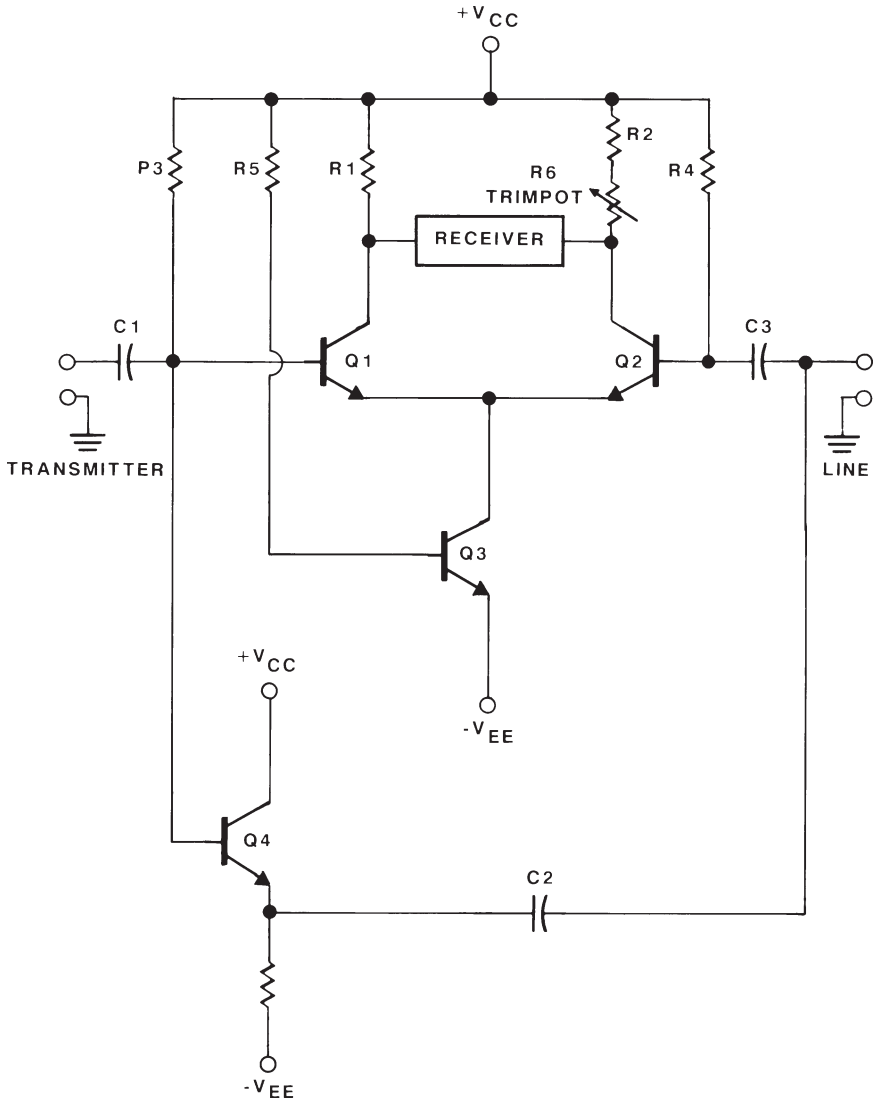


Figure 2-6

IC voice network.

The transmit signal is applied to the base inputs of Q1 and Q2. Emitter-follower Q4 provides unity voltage gain (a gain of 1.0), and 0° phase shift. The transmit signal is applied to the base input of Q4. The emitter output of Q4 drives the telephone line with an outgoing voice signal, as well as applying this same signal to the base input of Q2. With equal signal levels at the base inputs of Q1 and Q2, the transmit signal is identical at both collector terminals. With identical voltage levels, there is no difference in voltage across the receiver transducer, so no current flows through it. Slightly unbalancing the differential amplifier through trimpot R6 produces the small difference in collector voltages to provide sidetone to the receiver.

The incoming voice signal on the telephone line is applied only to the base input of Q2. This signal is isolated from the base of Q1 by the reverse-connected common-collector amplifier Q4. All of the amplified incoming voice signal appears as a difference voltage across the receiver terminals; at the Q1/Q2 collector outputs of the differential amplifier.

THE DIAL

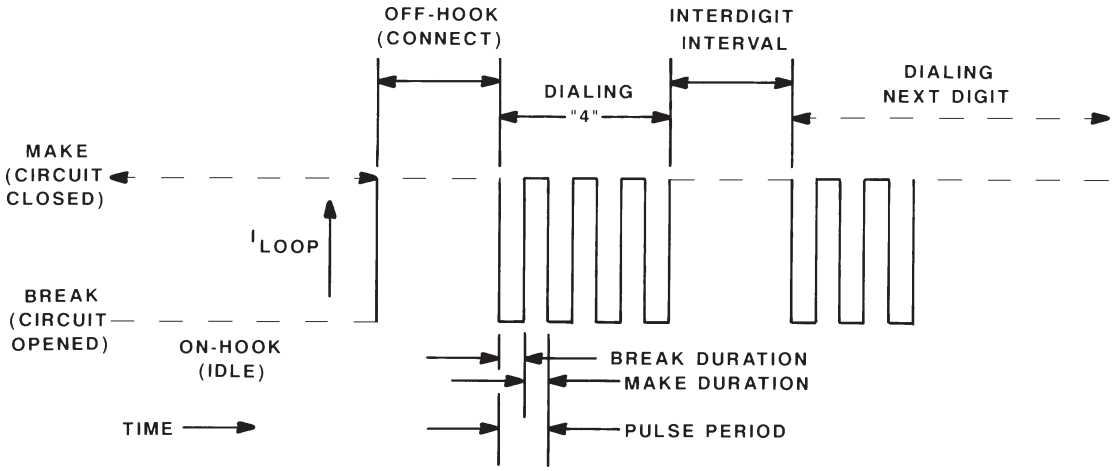
There are two forms of dial signals that activate the central office's switches. These are dial pulses, and dial tones. The dial pulses are produced simply by interrupting the DC path between the hookswitch and the network. Dial tones are a combination of two frequencies for each digit that signal and activate the central office's switches. The standards for both pulse and tone dialing are critical, to prevent falsely activating the central office switch, or dialing incorrect telephone numbers. Tone dialing is a far faster and superior technique of dialing. However, the PTN maintains both pulse and tone capabilities to accommodate the large number of rotary dial telephone sets still in use.

> Telephone dialing is accomplished with a sequence of pulses, or with a combination of two tones, for each digit in the telephone number dialed.

The rotary dial is a mechanical switch that sequentially opens and closes its contacts as it rotates. It is spring-loaded to return to its starting point for each digit entered. The switching mechanism of the dial is active only on its return rotation, where its speed is governed to comply with the timing standards of the telephone system. The rotary dial breaks contact once for each digit dialed; so dialing 7, for example, results in a sequence of seven on-off current pulses on the telephone line to the central office.

Pulse dialing can also be obtained from electronic switches that are activated by the push buttons on a dial pad. Pressing button 7 on the pad, for example, causes a circuit to produce a sequence of seven on-off current pulses, similar to those obtained from a rotary dial telephone. Most dial-pad pulse circuits are used in combination telsets that have both pulse and tone dialing options, and where the keypad layout for both dialing functions are identical.

The nominal pulse timing standards are illustrated in Figure 2-7. The standards specify limits on pulse rate, pulse period, and the inter digit interval. In electrical terminology, the word "duty cycle" can also be used to identify the property of the pulses. Duty cycle describes another dimension of a pulse that is related to its pulse rate and its pulse period. That is, duty cycle is the ratio between the dial pulse's make (contact) time and its break (open) time.



PULSE PERIOD=BREAK DURATION+MAKE DURATION(100 MILLISECONDS NOMINAL)
PULSE RATE=PULSES PER SECOND=1000 ÷ PULSE PERIOD (ms)
PERCENT BREAK=100xBREAK RATIO
=100xBREAK DURATION ÷ PULSE PERIOD
INTERDIGIT INTERVAL=700msNOMINAL(600 TO 900 ms)

Figure 2-7

Dial-pulse timing.

For rotary-dial telephones, the nominal pulse period is specified at 100 milliseconds (0.1 second). The pulse rate is the reciprocal of the pulse period, specified at ten pulses per second. The duty cycle is 0.6 to 0.7 (60% to 70%). In telco jargon, the duty cycle is sometimes called "percent break," to describe the time that the rotary-dial switch breaks contact. Finally, the time between dial pulses, called the "interdigit

interval," is specified at 0.6 to 0.9 second. This is the minimum time period required to indicate the next digit of the telephone number. Recall that the maximum interdigit interval is about 15 seconds, which is the time period that causes a disconnect and an advisory signal request for redial.

Both the ringer and receiver circuits of the non-electronic rotary-dial telephone are disabled when the dial is rotated. If they were not disabled, the dial pulses would create voltage "spikes" that would make annoying pops in the receiver, and even "tinkle" (softly ring) the ringer's bell. This switch circuit is called "anti-tinkle and speech muting." The circuit includes a capacitor to suppress spikes, a load resistor for the ringer's inductor, and a set of contacts, called "off normal" contacts. The off-normal contacts bypass (shunt) the receiver connections to disable its operation during dialing. Figure 2-8 shows the switch contacts of this circuit as a part of the rotary dial mechanism.

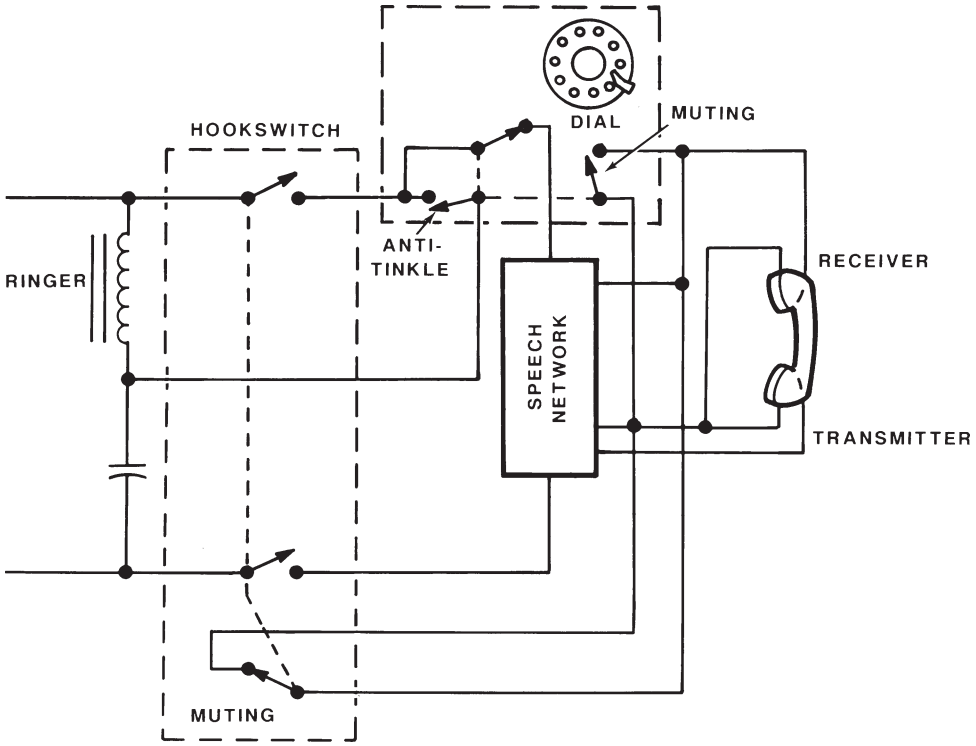


Figure 2-8

Anti-tinkle and speech muting.

Tone Dialing

Tone dialing is activated by push buttons on the telset's dial pad. This method of dialing is called "dual-tone multi-frequency," and is abbreviated DTMF. Each of the push buttons on the DTMF dial pad control a pair of frequencies. Different frequencies are assigned to each of the columns and rows of the dial pad. Each button pushed, therefore, sends a distinct pair of frequencies to the central office switch. The central office switch then translates the tones to an equivalent number location in its register. Figure 2-9 shows the arrangement of the numbers on the pad, and the frequencies they activate. The standard keypad of Figure 2-9A shows 12 push buttons and their associated frequencies. Figure 2-9B shows an extended keypad of 16 push buttons. The 16-button dials are not yet standard, but the frequencies are available in the telsets and central office switches to accommodate future extended dialing needs.

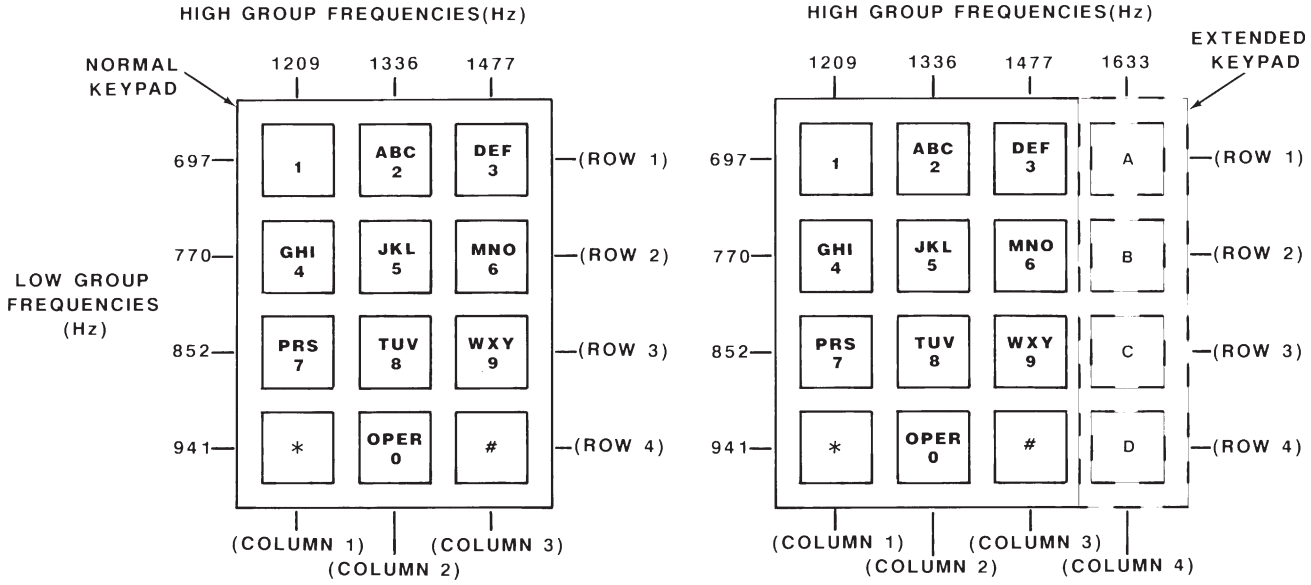


Figure 2-9

DTMF frequencies.

Depending upon the design of the telset, the DTMF frequencies can be generated by LC networks and a simple transistor oscillator, or by a self-contained digital IC device that creates the frequencies by dividing down a single higher-frequency clock signal. Figure 2-10 shows two general variations of these circuits. With either design, the DTMF tones must be precise, within 2%, to activate the central office switch. The columns of the dial pad activate high-group frequencies: 1209,

1336, 1477 1633 Hz. The rows activate low-group frequencies: 697, 770, 852, 941 Hz. Pushing push button 7, for example, connects the two frequencies 852 and 1209 Hz that cross this digit, and applies them as an output signal on the line to the central office. These tones are heard as a sidetone in the telset's receiver, just as voice signals are heard.

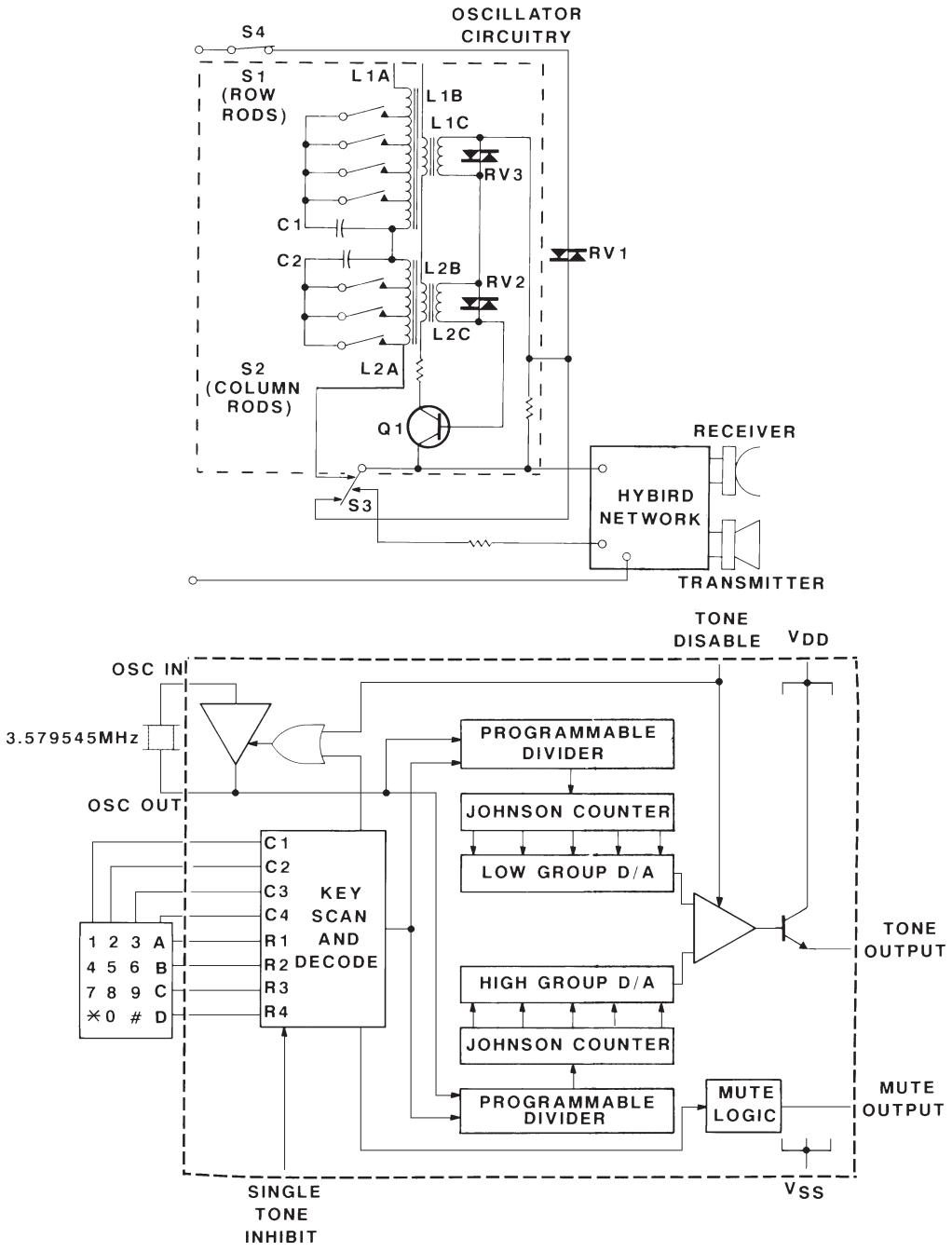


Figure 2-10

DTMF circuits.

The primary advantage of DTMF switching is time. The minimum time required for the DTMF tones to register in the central office switch is 50 milliseconds, and the interdigit interval time, the time between tones, is also 50 milliseconds. With these standards, a nine digit (long-distance) area call can be dialed in less than one second with automatic dialing equipment. (Humans are slower!) Recall that with a rotary-dial telephone, each of the digits require a string of 100 millisecond pulses with a minimum interdigit interval time of 600-to 900 milliseconds. With high-numbered digits, the rotary dial telset requires at least ten seconds, with automatic dialing, to dial a nine-digit number.

> The primary advantage of DTMF switching is time. With DTMF, a nine-digit telephone number can be dialed in less than one second.

Aside from precise frequencies, the levels of the DTMF signals must be generated within specific power limits to correctly activate the central office switch. The low-group frequencies are nominally at levels of –8 dBm, while the high-group frequencies are at levels of –6 dBm. The high-group frequencies are at power levels 2 dB higher than the low-group to compensate for the increased high-frequency losses that occur along the transmission line between the telset and the central office.

Finally, an additional requirement for the DTMF tones is low distortion. Recall that distortion produces harmonic and intermod frequencies in addition to the desired frequencies. These frequencies can cause errors in dialing. To reduce such errors, all harmonic and intermod frequencies resulting from distortion must be at least 30 dB be low (at 0.1% of) the power levels of the DTMF signals.

This concludes the detailed review of the single-line telephone set and its connection to the central office. The next chapter continues with a description of the detailed operation of the central office.

SUMMARY

Voice signals are transmitted from the telset by the carbon microphone. The current required for the carbon mike is provided by the central office's power source, called a "talk battery." The voice signals from the carbon mike are applied to the line, and the incoming line signal to the receiver transducer of the telset. A small amount of mike signal, called a "sidetone," is also applied to the receiver by the voice network.

In telephone industry jargon, the company that provides telephone services is called "telco." Telco uses signaling signals to operate its services. The indication of current flow when the telephone handset is lifted is a signal, a request for service. The dial tone is a signal to the calling party to begin dialing. The dial pulses, or dialing tones, are also signals that access the central office's switch to connect a caller's telephone with the telephone of the called party. Other signals inform the called of a busy line, or of other conditions that prevent a call from being completed. Signals also activate the business accounting functions of telco's operation.

SELF-TEST REVIEW

1. List the four main physical parts of the single-line telephone set.
   _____
   _____
   _____
   _____

2. List the six main electrical parts of the single-line telephone set.
   _____
   _____
   _____
   _____
   _____
   _____

3. Which component in the ringer network prevents direct current flow from the central office when the handset is on hook?
   _____

4. What frequency and range of rms AC voltages will the ringer operate? _____

5. List the four terminal connections of the telset's voice network.
_____
_____
_____
_____

6. For which signal are the voice network transformer's two receive windings out-of-phase?

   A. Incoming line receive signal.
   B. Outgoing transmit signal.
   C. Signal at the receiver.
   D. Signal at the balance circuit.

7. In the IC voice network, which signal is applied to *both* differential inputs?

   A. Incoming line receive signal.
   B. Outgoing transmit signal.
   C. Signal at the receiver.
   D. Signal at the balance circuit.

8. Given the standards for pulse dialing, what is the shortest time required of an automatic dialer to call the number, 767-2676?
_____

9. Given the standards for DTMF dialing, what is the shortest time required of an automatic dialer to call the number, 767-2676?
_____

10. Which frequencies are **NOT** used for DTMF dialing?

    A. 697 and 1336 Hz.
    B. 750 and 1209 Hz.
    C. 852 and 1477 Hz.
    D. 941 and 1633 Hz.

CHAPTER 3 — Facilities, Telset, and Central Office Circuitry

INTRODUCTION

In the first part of this chapter, you will learn more about the external wiring of the telephone system from your telset to the central office and beyond. This includes the connection block you may have noticed on the outside or in the basement of your home, and how the system and your home are protected from lightning strikes. You will also learn about the standard colors in a residential telephone cable and the purpose of each color wire.

Next you will learn how extension phones affect the loading of the telephone circuits and how to calculate total resistance and loop network current. Too many extensions phones off hook at the same time can reduce voice signals to an unsatisfactory level.

Third, you will learn more about both conventional and electronic telephones. Included in this discussion is a list of specifications for a typical telset and their minimum and maximum values.

Finally, you will learn more about the central office and how it communicates with the rest of the system.

OBJECTIVES

When you complete this chapter, you will be able to:

- Identify the name, function, and operation of each of the functional parts of a telset, central office, and local facilities.
- Specify the operating voltages, currents, and frequencies of the central office and telset required for proper operation of local telephone services.
- Specify the wiring connections between the local central office and telset for proper operation of the telephone services.
- Describe the proper connection of extension telephones off of a single wire-pair, and calculate the loading affected by their operation.
- Calculate the relationship between loop resistance, and the operating voltage and current available to a single-line telset.
- Describe the detailed operation and function of each component in the electronic single-line telset.
- Describe the functional operation of each section of the electronic single-line telset.
- List and describe the purposes of each of the central office functions that are activated by the loop relay.
- Describe loop-start and ground-start operation of local telephone services.
- Identify and describe the effects of signal-conditioning along telephone lines and circuits.
- Describe the character of lineside and trunkside wiring and circuits used from one telset, through a central office, and the long-haul network.
- Describe the detailed operation and functions of a 2/4-wire converter.

CONNECTION THROUGH FACILITIES

In industry jargon, the circuits and paths that interconnect locations and telephone equipment are called "wire, or cable, networks." Standard single-line and multi-line telsets connect to the central office through a wire network called "local loop facilities." The local loop facilities for each central office provide a separate telephone line for connection to each of the individual four-digit telephone numbers served by the central office.

Each of these telephone line wire-pairs are bundled into large multi-wire cables that serve a particular zone. When the cables reach their zone service area, the individual lines are extracted and distributed to the telephones in that zone. Each of the lines is an independent series circuit, a loop, that remains electrically separate from the other wires in the cable throughout the circuit path.

> A separate telephone line connects from the central office to each subscriber's location with an individual four-digit telephone number for each line.

The word "termination" is used extensively in the interconnection of telephone facilities equipment. As the word implies, a termination is merely the end of a wire or cable. In the path from the central office to the telset, the first termination is where the individual lines are extracted from a large multi-wire cable, at a termination box. This is the termination of that portion of the large cable, but not the termination of the local loop circuit.

This termination box is sometimes called a "junction box." It is the junction which connects the wiring in a residence or business, to the wires in the cables to the central office. A typical central office cable may include as many as 2000 wire-pairs, divided in 500 pair and 100 pair bundles. Each of the bundles will terminate in a junction box at the street, or at a large business address. It is from this junction box that wire pairs are run to the final termination of the loop, the telset.

Figure 3-1 shows the central office cable which connects to termination boxes and to residential locations. Each telephone line connects to a residence through a lightning protector and single-line terminal block. For business and multiple-unit dwellings, many lines connect to multiple-line terminal blocks, through lightning protectors. The lines from each of the telephone sets connect to their respective central office lines at the terminal blocks.

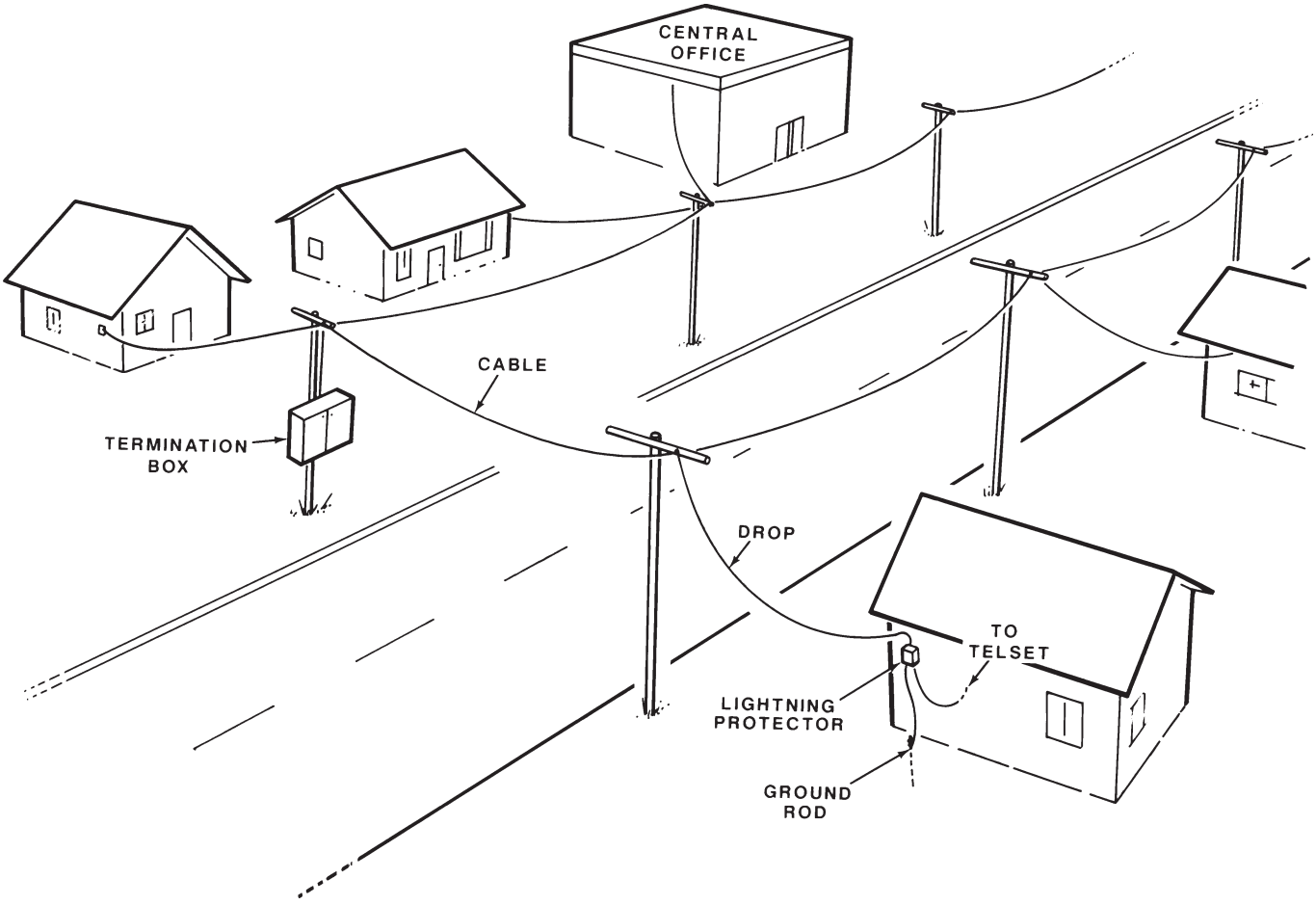


Figure 3-1

Residential facilities.

Single-line telephones are usually connected to the terminal block with a single wire-pair that terminates in a jack for plug-in access by a telephone line cord. For multi-line and key telephones, larger cables with many wire-pairs connect to the terminal block. The larger cables, of 6 to 100 or more wire-pairs, usually connect to these telephones through a multi-wire connector. Figure 3-2 shows the generalized connection of these telsets to the incoming lines.

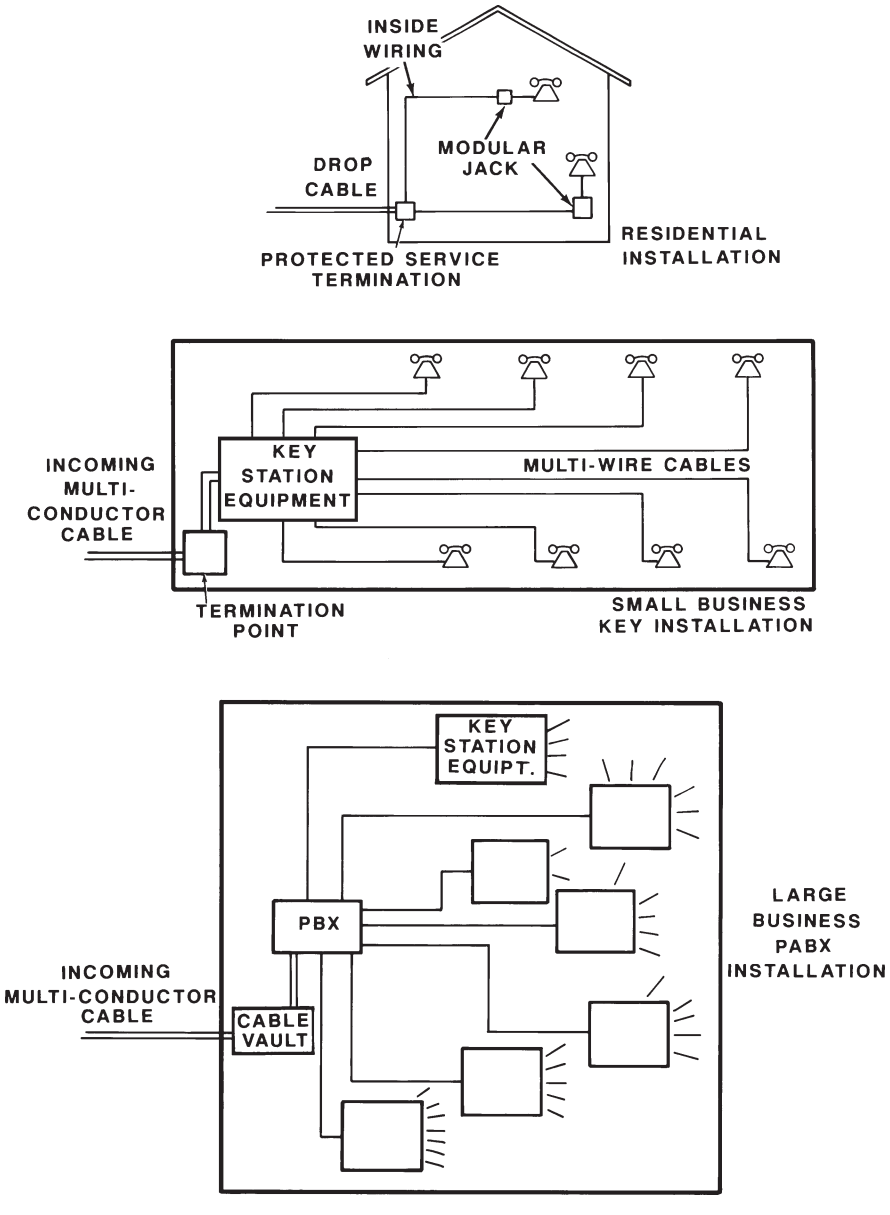


Figure 3-2

Telephone installations.

Loading Telephone Circuits

Multiple telephones, connected from a single-line termination, are extensions of the same wire pair and telephone number. In residential service, these telsets are often called "extension phones." These extensions should not be confused with PBX services, where extensions with distinct extension numbers are switched from a main business number. Residential extension telephones are connected in a parallel arrangement, so the extra telsets present an increased load to the central office's talk-battery power supply. The number of extension telsets added to a loop terminal in this way is not critical, so long as they are on-hook. However, the number of telsets off-hook at one time is critical.

Figure 3-3 shows the equivalent circuit of four extension telsets which terminate a loop circuit. Each telset has approximately 200 ohms DC resistance. For this example, we'll assume a typical loop resistance of about 1000 ohms, and 48 VDC supplied by the central office's talk battery.

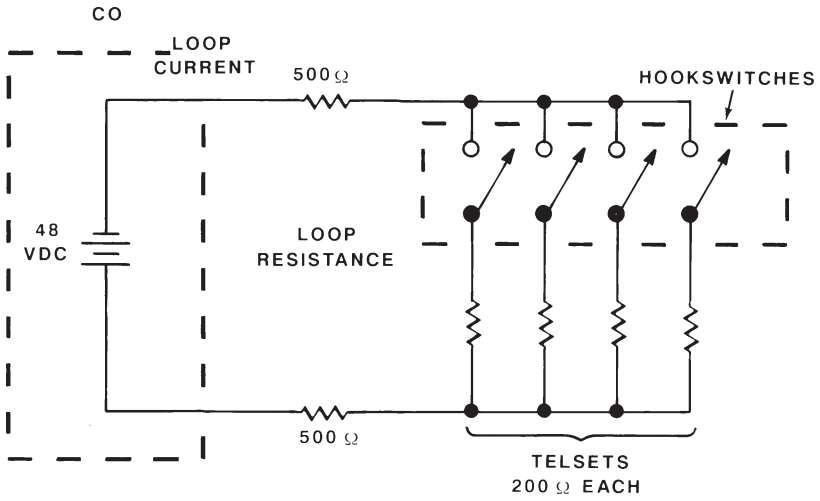


Figure 3-3
DC loading of telsets off-hook.

The loop network current can be calculated as follows for each telset that is off-hook:

$$I_{Load} = E \div (R_{Loop} + R_{Load})$$

For one telset off-hook, R_{Load} = 200 ohms

$$I_{Load} = 48 \div (1000 + 200) = 40 \text{ mA}$$

For two telsets off-hook, RLoad = 100 ohms

$$I_{Load} = 48 \div (1000 + 100) = 44 \text{ mA}$$

44 mA for two telsets = 22 mA for each telset, so both telsets will function satisfactorily.

For three telsets off-hook, R_{Load} = 67 ohms

$$I_{Load} = 48 \div (1000 + 67) = 45 \text{ mA}$$

45 mA for three telsets = 15 mA for each telset, so each telset will function marginally.

For four telsets off-hook, RLoad = 50 ohms

$$I_{Load} = 48 \div (1000 + 50) = 46 \text{ mA}$$

46 mA for four telsets = 11.5 mA for each telset, so the telsets will not function properly.

As you may conclude, using extension telsets simultaneously depends upon the loop resistance between the central office and the terminal. Using the procedures of the above calculations, a loop resistance of less than 400 ohms allows simultaneous operation of four extensions for a recommended minimum current of 20 milliamps-per telset. A loop resistance of 1800 ohms allows only one telset to be off-hook at one time.

In addition to affecting increased loading, the operation of telsets in parallel reduces the level of the voice signals on the line. The received voice signal drives two, or more telsets, and the transmitted signal drives two, or more telsets. The power generated by the transmit transducers is divided among the loads wired in parallel across the line.

For DC loop current, the parallel connection of extension telsets is not usually a problem, as long as only two sets are off-hook at any one time. Recall, however, that the ringer circuits of all telsets always load the loop, as they are connected to the line ahead of the telset's hookswitch. Also recall that the ringer network includes a DC blocking capacitor, so it is activated only by an AC signal.

Fortunately, the load of the ringer is *not* a problem when extension telsets are connected in parallel with the telephone line, as the impedance of the ringer network is high. The typical ringer impedance is about 6000 ohms, with the telset connected for a 20 Hz ring signal, and it is about 3000 ohms with the telset connected for a 30 Hz ring signal.

The rms voltage of the ring signal from the central office is in the range of 90 VAC. The telset ringer will function with voltages as low as 40 VAC. With a load impedance in the range of 6000 ohms, and 1000 ohms loop resistance, as many as six ringers can be connected in parallel and only reduce the ring signal to half its level from the central office. Figure 3-4 shows this equivalent circuit.

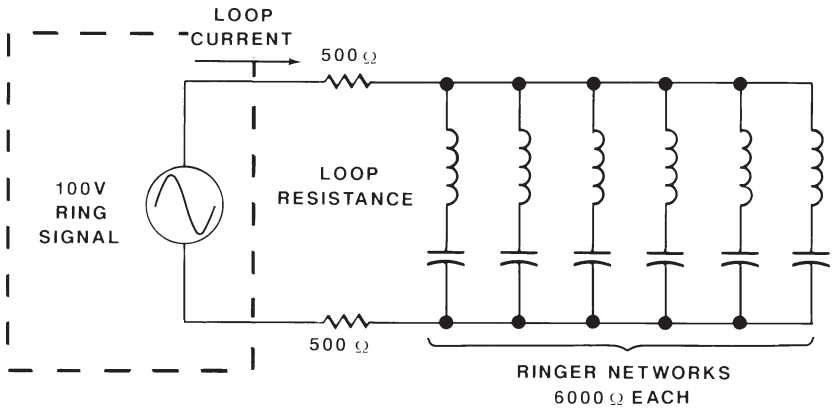


Figure 3-4

AC loading of telsets on-hook.

In addition to the extension arrangement, many installations need multiple telephone services. Businesses often require extensive internal communication between offices in single or multiple locations. If such multiple telephones were to be operated from single central office loops, the loading would be excessive and far beyond the capacity of the central office's talk battery power supply. Multi-telset operation thus requires operation power-independent of the central office, but with complete signal access to the central office.

Key telephones, private line equipment, and PBX terminals are examples of business and multi-unit installations requiring independent talk-battery power for internal communication. This type of terminal equipment operates with auxiliary power which is independent of the central office, but with access to a local loop, so voice and other signals may pass to and from the central office's lines.

Station Wiring

A station is a location where telsets are installed. Station wiring to single-line telephones consists of two wires: a red wire, identified as the ring, and powered with negative DC voltage; and a green wire, identified as the tip, which is the positive-grounded return lead. (Remember that the tip lead is not directly grounded.) This red and green wire-pair connect directly to the telset.

Very often, an additional wire-pair is included in standard residential station cable. These wires are yellow and black, and they are available as a spare wire-pair. This second pair may be used to replace a failed wire-pair; and it may be used for other power applied to the telset, or for a convenient connection of two separate lines to a residence. The yellow-black wire pair may also be used to power lamps in telsets if they are required to light push buttons, dial plates, or indicate operation of the phone. The lamps are powered through the yellow black wire-pair that connect to a transformer or auxiliary power source located at the residence or business.

THE TELEPHONE SET

Figure 3-5 shows the schematic and wiring diagram of a typical nonelectronic residential rotary-dial telephone. The diagram also shows standard terminal coding, and standard wire color coding. The input line to the telset is available through the terminal block entering the residence, through interconnecting wiring, and a modular block where the telset's line cord is connected.

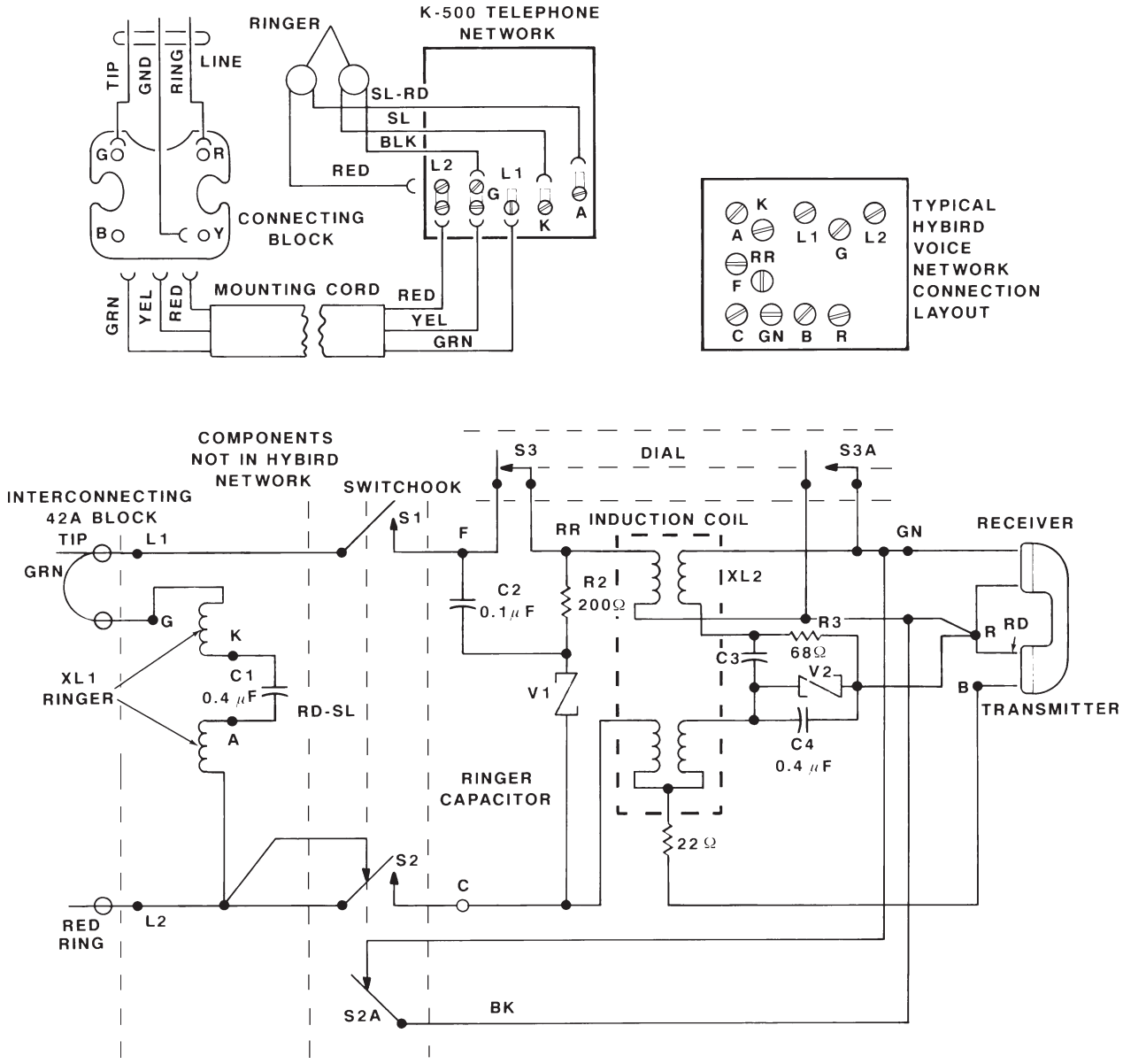


Figure 3-5

Circuitry of conventional telset.

The green tip wire is attached to terminal L1, where it connects to one side of the hookswitch (S1). There is a jumper wire from terminal L1 to terminal G, which connects the ringer network to the line. The red ring wire is attached to terminal L2, where it connects to the other side of the hookswitch (S2). The diagram shows the hookswitch contact wired back upon itself to the red wire of the ringer network. While the switch contact serves no purpose here, this arrangement allows for alternate ringer connections that are not used in this telset.

The ringer is a series-resonant LC network comprised of two bell clapper solenoids, XL1, and the 0.4 microfarad capacitor, C1. The capacitor is connected to terminals A and K. The network is resonant at 20 Hz, and the total inductance can be calculated as:

$$L = \frac{1}{(2\pi f)^2 C} = \frac{1}{(2\pi \times 20)^2 \times (4 \times 10^{-7}) = 160H}$$

$$L = 1 \div [(2\pi \times 20)^2 \times 4 \times 10^{-7}] = 160H$$

Each of the coils is half the total inductance of 160 henrys, or 80 henrys each. This inductance value is high, but is required to develop the magnetism necessary to loudly ring the bell clapper. Bypassing one of the coils, with a jumper from K to G will reduce the total inductance to 80 Henrys, and raise the resonant frequency of the ringer network to about 30 Hz.

The wire from hookswitch S1 connects to terminal F, and then to dial switch S3. The contact of S3 connects to terminal RR and the voice network. Capacitor C2 couples the voice signal to component V1. V1 is a varistor, a voltage-varying resistor. The internal resistance of the varistor changes in inverse proportion to the voltage across its terminals.

In this circuit, the varistor provides a lower resistance load, (in series with the 200-ohm resistor, across telephone line terminals RR and C when signal levels are high. The varistor, therefore, compensates for differences in voice signal levels between telsets that are nearby with those that are farther distant. The high-level voice signals from short-distance transmission paths are automatically reduced so they don't sound too loud.

Terminals RR and C connect the incoming line to voice network XL2. The outputs of the voice network connect to the receiver at the GN and R terminals, to the transmitter at the B and R terminals, through the 22-ohm limiting resistor, and to the balance network. We reviewed the operation of the voice network in a previous section. The balance

network is comprised of resistor R3, capacitors C3, and C4, and varistor V2. The varistor in the balance network reduces the sidetone level when the speech level in the transmitter is high, and raises the sidetone level when the speech level is low.

Dial switch contacts S3 and S3A are opposite in action. When S3 opens and breaks the loop current path, S3A closes to prevent the dial click from being heard in the receiver. Likewise, hookswitch S2A closes when activating the hookswitch, to prevent that click from being heard in the receiver.

You may recall that the transmitter is a carbon microphone, with a high sensitivity of about 0 dB. Also recall that the receiver is an efficient dynamic earpiece, with an efficiency above 110 dB SPL/watt. With such high sensitivity and efficiency, the transmitter and receiver operate without amplification in the basic telephone set. Condenser "mics" are often used in electronic telsets in place of the carbon "mic". Audio amplification is required with the condenser "mics".

Table 3-1 summarizes the operating characteristics of the telset operating in the local loop. Both the nominal desired values and their limits are listed. Perhaps the most significant observation you can make about the telset, after reviewing this Table, is that it will function over a very wide range of operating conditions.

Table 3-1

Operation of telset in local loop.

ITEM	TYPICAL U.S. VALUES	LIMITS
Talk-Battery Voltage	-48VDC	20-100 VDC
Operating Current	20-80 mA	20-120 mA
Loop Resistance	600-2200 Ohms	400-2200 Ohms
Ringing Signal	20/30 Hz, 50-80 VAC	16-60 Hz, 40-130 VAC
Loop Signal Loss	8 dB	18 dB
Received dB_{SPL}	70-90 dB	60-130 dB
Noise (ref. 0dBm)	-75 dBm	-60 dBm
Distortion	-50 dB	-30 dB

The telset is a versatile instrument that operates over the wide range of currents and voltages which are available from the central office power source.

Electronic Telephones

The advances of current technology have been applied to the telset, as well as to other aspects of telecommunications. The telset is an ideal application for electronic microcircuits, as the potential market volume justifies heavy expenditures in sophisticated product development. Each of the component parts of the telset are available as IC devices, and there are even IC devices that provide all of the telset circuit functions in a single chip. In addition, many specialized features are available to enhance the operation of the telset, including: recording, dial memory, call-forwarding, paging, speakerphone, and others. All of these features are practical as a result of the specialized electronic microcircuits which have been designed for telephone services.

> The telset is an ideal application for IC microcircuits, as its production volume justifies heavy engineering expenditures.

Figure 3-6, on the next page, shows the general block diagram of an electronic telephone set. This circuitry includes all of the functions of the simpler electrical telset described earlier. The functions include a hookswitch, dialer, ringer, voice network, receiver, and microphone (transmitter). In addition, the electronic telephone has power supply circuits to operate its transistor and/or IC devices.

Like the simple electric telset, the electronic telephone obtains its power from the central office's talk battery, through the telephone line. The full-wave bridge rectifier, D1 through D4, at the tip and ring inputs of the telephone line assure that the polarity of the DC voltage applied to the telset is positive. Recall that the tip terminal is the positive green wire, and connects to ground at the central office. The ring terminal is the negative red wire, that connects to the negative DC source at the central office.

With the tip positive, and the ring negative, D2 and D4 conduct, which grounds the negative line at the telset, and directs the positive voltage to its hookswitch input. If the tip and ring terminals are interchanged, D1 and D3 conduct, and result in the same negative ground and positive input to the telset. The electronic components within the telset require a positive DC voltage for operation. The bridge rectifier assures this connection regardless of how the tip and ring terminals are attached to the telephone.

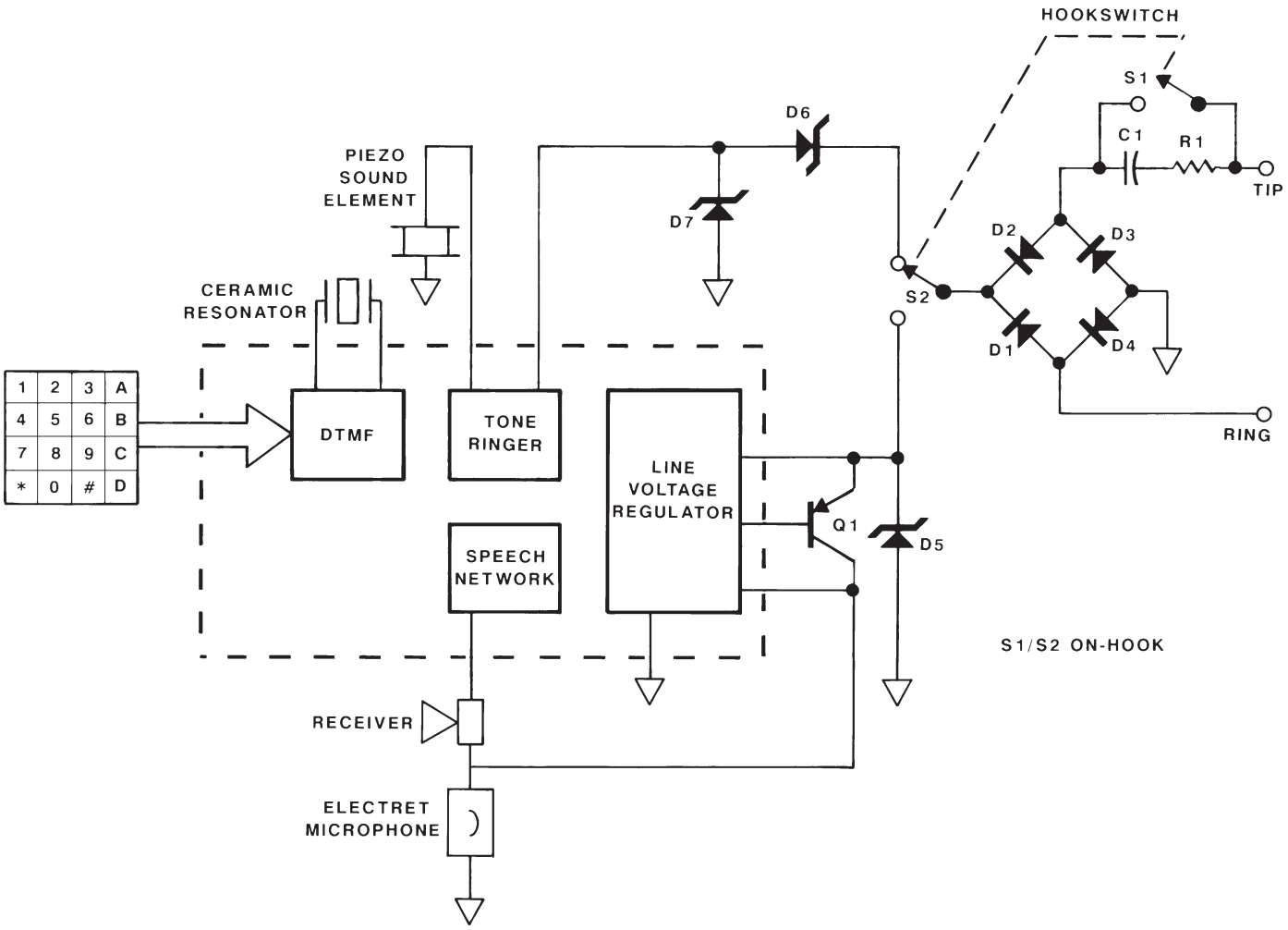


Figure 3-6

Circuitry of electronic telset.

Figure 3-6 shows the hookswitch (S1/S2) drawn with the handset on-hook, and the line connected to the ringer circuit. R1 presents a high-impedance load to the line, and C1 blocks DC. When a ring signal is applied to the line, it passes through R1 and C1, and is rectified by D2. The resulting high-voltage ring signal is applied to the tone ringer. D6 and D7 clip the minimum and maximum levels of the ring signal to the voltage limits of the ringer circuit. The output of the ringer is a piezoelectric output transducer.

When the handset is off-hook, the DC bypasses R1 and C1 and connects directly to a voltage-regulator circuit. Recall that the conventional electric telephone is a current-operated instrument. The electronic telset however, is voltage operated, so it requires the line voltage regulator to obtain fixed operating voltages from the central office.

Like all speech networks, the speech network in the electronic telset is a duplexer that directs incoming line signals to the receiver, and outgoing transmitter signals to the line. Sidetone circuitry is also included in the network. Recall that the detailed operation of an electronic speech network, the electronic hybrid, was described earlier.

The DTMF encoder circuit operates in conjunction with a high-frequency ceramic resonator (crystal). The circuit includes digital circuitry with frequency dividers to obtain an exact set of the eight distinct DTMF frequencies. These frequencies are selected by the dial keypad, and applied to the voice network, like a voice signal from the microphone. The dial tones are then output to the telephone line, with sidetone applied to the receiver.

Cordless Telephones

With an ordinary telephone, the length of its cord limits your movement, or where you can use it. You may be able to install jacks in other rooms in your house, but this usually isn't practical outdoors. In addition, jacks in other rooms do not help much if you need to move about during a telephone conversation. Cordless telephones, however, provide you with a relatively inexpensive way to get around the cord problem.

Cordless phones are made up of two major components: the handset and the base unit (see Figure 3-7 on the next page). In a typical installation, cordless phones have a range of several hundred feet. You can usually increase this range by connecting the base unit to an external antenna. Many cordless phones have a variety of features available, such as redial, memory, paging, intercom, and a find function. The intercom function allows you to talk between the two units, while the find function produces a loud tone to help you locate a misplaced handset.

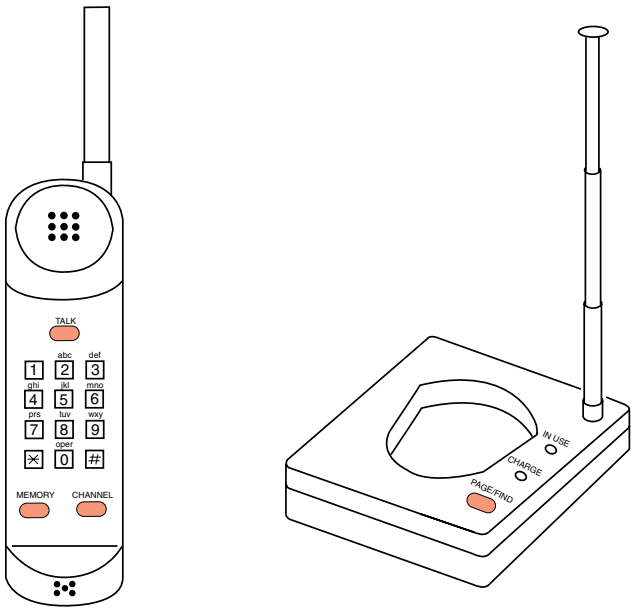


Figure 3-7

A typical cordless telephone system.

The handset typically contains two transducers (microphone and speaker), a keyboard, an AM or FM transmitter, and an AM or FM receiver. Some handsets do not have a keyboard and are designed to be worn on the head. These devices provide even greater freedom by allowing you to move about with both hands free. Newer cordless handsets may include a display which provides a caller ID feature, as well as show the number you have dialed. They may also have a call-waiting feature and allow you to switch between two phone lines. Like wired-in phones, the caller ID and call-waiting features are premium services that require an additional monthly fee.

The base unit typically contains an AM or FM transmitter, an AM or FM receiver, and the electronics necessary to control the operation of the system and connect to a telephone line. They also usually contain a simple power supply to operate its circuitry and to charge the handset's rechargeable battery.

As mentioned above, the handset and base unit each contain a transmitter and receiver. These circuits provide the wireless link between the two units as shown in Figure 3-8. Older cordless phones used the AM mode and two widely separated frequencies, 1.7 MHz for the base-to-handset link and 49 MHz for the handset-to-base link. Due to

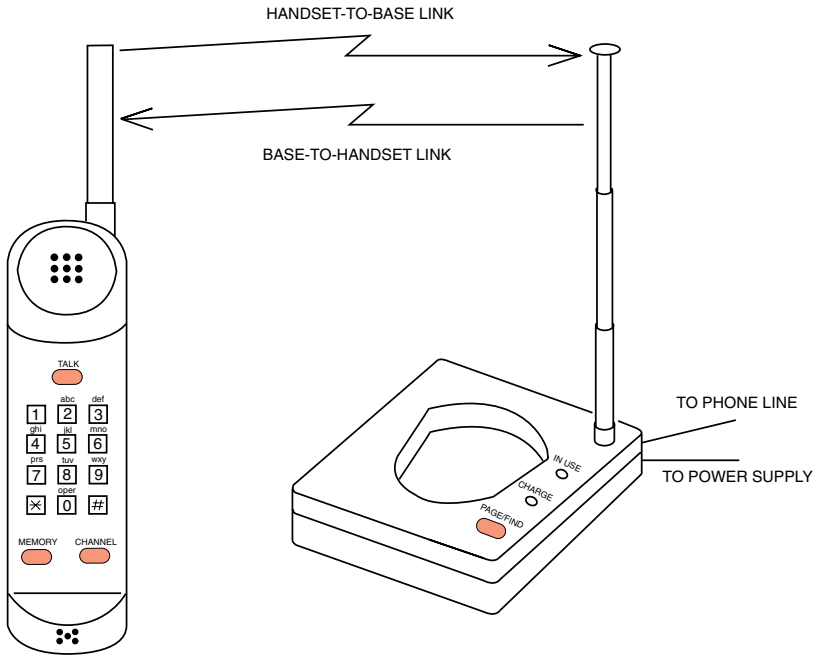


Figure 3-8
Wireless link.

problems with noise and interference from other electronic devices (including other cordless phones on 1.7 MHz), cordless phones eventually switched to the FM mode (for its inherent noise-free operation) and allow you to select any one of ten channels for paired multiple-channel flexibility as shown in Table 3-2.

Table 3-2

CHANNEL	BASE (MHz)	HANDSET (MHz)
1	46.610	49.670
2	46.630	49.845
3	46.670	49.860
4	46.710	49.770
5	46.730	49.875
6	46.770	49.830
7	46.830	49.890
8	46.870	49.930
9	46.930	49.990
10	46.970	49.970

With this arrangement, 10 channels between 46.61 MHz and 46.97 MHz are used for the base-to-handset link, and 10 channels between 49.67 MHz to 49.99 MHz are used for the handset-to-base link. Cordless phones generally have a provision that allows you to select the channel you want, usually the one that is the most interference free. Two separate frequencies are used to provide full-duplex operation so that each party can talk and listen to the other person at the same time (just like with an ordinary phone). Each frequency is modulated with the voice conversation and control data between the two units. In addition, the base-to-handset link also contains a sidetone so the person at the handset can hear his own voice. In fact, if you were to tune an FM receiver capable of receiving 46–47 MHz to the base-to-handset frequency, you would hear both sides of the conversation.

When the 10 channels mentioned above became crowded, 30 more channels were assigned to cordless phones as shown in Table 3-3. These are unpaired frequencies, meaning that the handset and the base can operate on any combination of the 15 frequencies allotted to each.

Table 3-3

BASE (MHz)	HANDSET (MHz)
43.72	48.76
43.74	48.84
43.82	48.86
43.84	48.92
43.92	49.02
43.96	49.08
44.12	49.10
44.16	49.16
44.18	49.20
44.20	49.24
44.32	49.28
44.36	49.36
44.40	49.40
44.46	49.46
44.48	49.50

Eventually, 40 more channels were allotted to cordless operation. These are much higher in frequency (902–904 MHz for the handset, and 926–928 MHz for the base unit). These phones typically use digital FM and some type of encryption (scrambling). They feature better reception, greater range, and better security, but are more expensive. Some use spread spectrum technology for even greater security.

The cheapest method of telephone security uses analog scrambling, but is easiest to unscramble. This method inverts the high and low audio frequencies and converts the audio to single sideband. You can hear the resulting audio signal, but it is just a bunch of unintelligible sounds.

Digital encryption and spread spectrum technology are more expensive than analog scrambling, but are much harder to unscramble. These systems produce a sound or noise that does not resemble speech.

The Electronic Communications Privacy Act (ECPA) of 1986 as amended makes it illegal to listen to cordless telephone conversations (in addition to some other types of transmissions), but it really just gives a false sense of privacy because it is almost impossible to enforce. The best way to reduce the chance of unauthorized listeners from intercepting your telephone conversations is to use an ordinary corded phone or a cordless phone with digital encryption. In any case, never say anything on a cordless phone that you wouldn't say in public.

THE CENTRAL OFFICE

A detailed study of the circuits within the central office is complicated far beyond the scope of this text. However, there are general circuit functions that can be studied individually to convey the electrical operation of this segment of the PTN. The same circuit functions that are present in the central office are also present in private branch exchanges (PBX) that serve government, business, and industry.

Figure 3-9 shows a simplified telset-to-central office diagram of the central office connection to the telset, excluding the complex switching circuitry. The talk battery power source is applied to the DC path from ground through one of the output winding pairs of transformer T1 that connects to the ring (R) line of the local loop. A current-sensing relay is placed in series with the DC path through the other winding of the transformer that connects to the tip (T) line of the local loop. This circuit provides power to the telset through the local loop, and senses an on-hook, off-hook, and/or ground condition in the DC circuit.

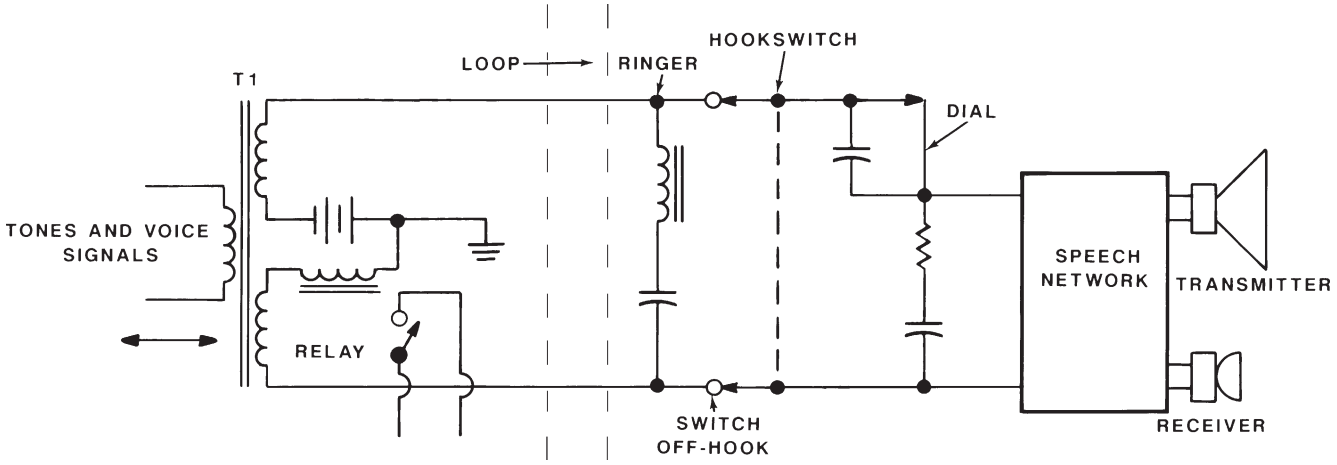


Figure 3-9

Generalized CO/telset circuitry.

The voice signals from the line to the telset couple through transformer T1 to the other circuits of the central office. The tone signals from the central office, and the incoming voice signals, couple in the opposite direction through the transformer and to the local loop.

The current-sensing loop relay in the tip line of the local loop controls a number of functions. This relay senses loop current as a DC signal, signaling signal, of the condition of the loop and telset to which it connects. The relay controls ringer, voice signal connection, and supervisory circuits within the central office. You may wish to review the "Sequence of Operation" described in Chapter 1, to identify all of the actions that occur from point of origin to completion of the telephone call. These operations depend upon the status of the loop relay.

Like all modern electronic circuitry, the loop relay can take the form of electronic or computer equivalents of the electromagnetic switch we call a "relay." In all cases, the function is simply to switch signals and operations that are activated by telset hookswitch and dial actions. The relay activates the following functions provided by the central office:

- Dial tone
- Switching services
- Ring generator
- Ringback tone
- Busy signal
- Advisory signals/messages
- Supervision of call

Table 3-4 summarizes the character of the tone signaling provided by the central office to the local loop.

Table 3-4

CO tone signaling to local loop.

TONE	FREQUENCIES	ON/OFF TIME
Dial	350 & 440 Hz	Continuous
Busy	480 & 620 Hz	0.5/0.5 Sec.
Ringback	440 & 480 Hz	2/4 Sec.
Reorder *	480 & 620 Hz	0.3/0.2 Sec.
Congestion (toll)*	480 & 620 Hz	0.2/0.3 Sec.
No Such Number *	200 to 400 Hz	Variable Freq.
Receiver Off Hook *	1.4k, 2k, 2.5k & 2.6k	Loud 0dBm Level

*These tones may include a recorded message.

Central Office Operation and Central Office Communication

Telephone service "starts" when the loop relay is activated. In telephone jargon, the word "start" is, therefore, used to identify the operation of central office services. For service to "start," a central office line must be "found" and "seized" from among those available to the caller's loop. The application of dial tone to the local loop verifies that the line is seized and extended to the first section of the central office's switch.

There are two ways that central office service is initiated: loop start, and ground start. Most single-line telephones are connected in the series loop path with their hookswitch normally open (on-hook). When the telset goes off-hook, the loop is closed, loop current flows, and central office service is initiated. This process is called "loop start," as service begins when the loop circuit is closed.

Most PBX and other equipment that operate independently of local loop power use another way of obtaining central office service. To seize a line, this equipment momentarily grounds the ring (red, negative voltage) terminal of the line from the central office. Grounding the line causes current to flow, and central office service is initiated. This process is called "ground start," as service begins when the current-source side of the loop circuit is grounded. Ground start has a higher loop current than loop start, because with loop start, the current is limited by the return-path resistance, while with ground start, the current returns through ground.

The central office is a two-way exchange. It accepts signals from the telset and from other exchanges, and it delivers signals to the telset and to other exchanges. When you refer to the two sides of the switch, it is more correct to use the terms "lineside" and "trunkside" rather than "input" and "output." For the outgoing voice signal from the telset, the input side of the central office is the lineside, and the output side of the central office is the trunkside. For an incoming voice signal, the input side of the central office is the trunkside, and the output side of the central office is the lineside.

The lineside of the central office is comprised of two-wire local loop circuits. Signals pass in two directions on the same wire pair. By contrast, the trunkside of the central office is most-often comprised of four-wire circuits. With four-wire circuits, signals flow only in one direction on each wire pair, so two wire pairs are required for two way transmission. Figure 3-10 shows the connection with the trunkside of the central office. The hybrid 2/4-wire converters separate the incoming and outgoing signals to and from their respective wire pair.

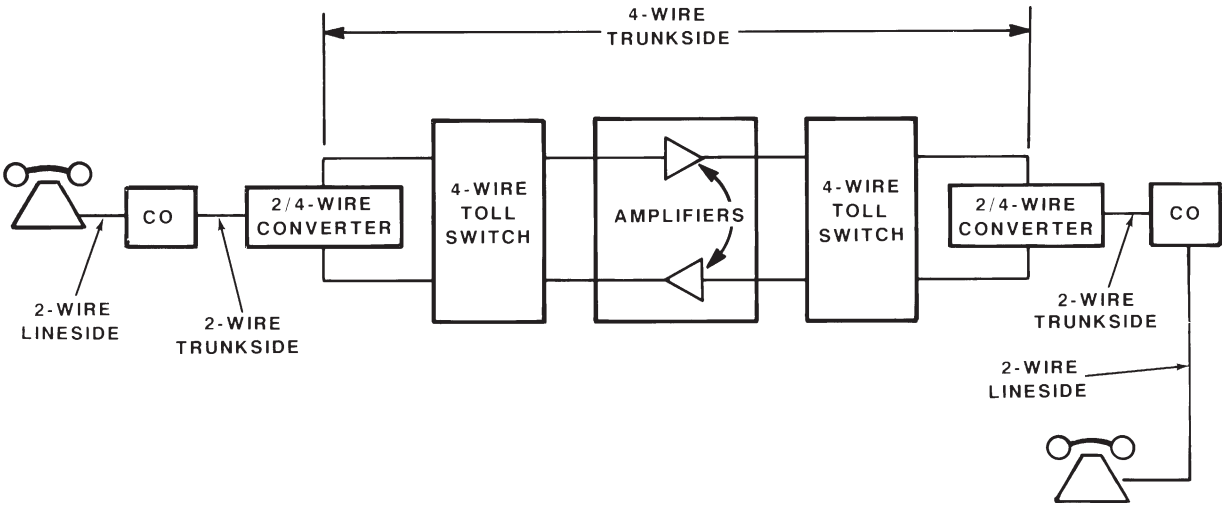


Figure 3-10

CO/CO circuits.

4-wire lines (circuits) are used primarily in longer-distance circuits for signal amplification or other signal conditioning. It would be most unusual if the origination and received signals are at identical levels through all of the circuit paths of a complicated telephone network. To adjust the level or frequency characteristics of one signal differently than the other requires that the signals be separated into two, one-way circuits.

2/4-wire conversion is a definite requirement when telephone signals are to be amplified. Amplifiers are one-way devices. They increase the level of signals from their input-to-output terminals, and they don't pass signals in the reverse direction. 2/4-wire converters are, therefore, required to be used in conjunction with separate amplifiers in tended to condition, change the level and/or frequency response of, both incoming and outgoing signals. If the signal conditioning is to take place in two-wire circuits, two 2/4-wire converters are built into the components inserted into the 2-wire line. The details of signal conditioning, and other aspects of transmission, will be covered later.

The 2/4-wire converter is similar to the voice network of the telset. It is a duplexer that separates transmit and receive signals on a single line, into separate one-way signals on two separate lines. Figure 3-11 shows the general hybrid transformer connection of the 2/4-wire converter. Unlike the telset voice network, sidetones are undesirable in this network. The 2/4-wire converter must have perfect balance to completely cancel the unwanted signals from its adjacent terminals.

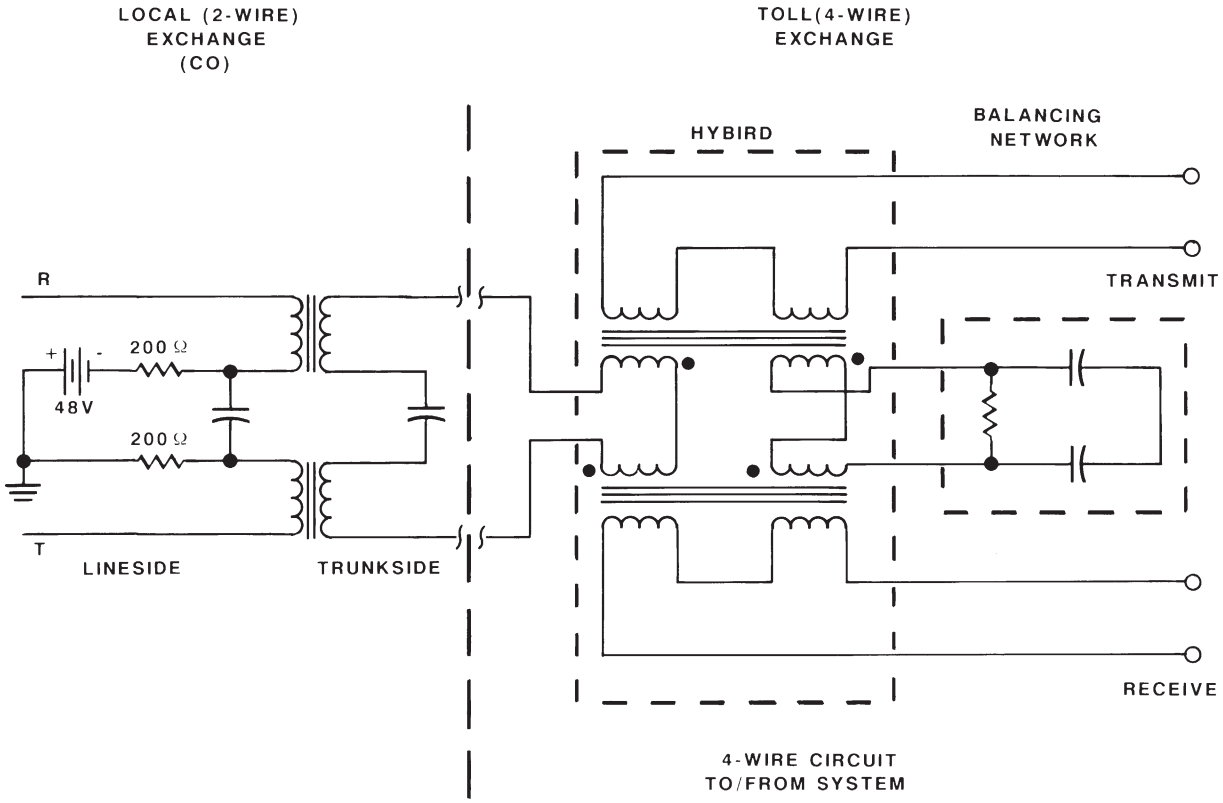


Figure 3-11

CO and hybrid 2/4-wire converter.

The 2/4-wire converter is a duplexer that separates transmit and receive signals on a single line, into separate one-way signals on two separate lines.

This concludes the text content of the chapters dealing with the Telephone System. The circuitry of the major parts of the system is described in the preceding chapters. These system parts include the central office, the facilities, and the terminal equipment used for telephone communications.

SUMMARY

In this chapter we concentrated upon the functional electrical circuitry within the telset, central office, and its facilities. As a piece of electrical equipment, the telset is crude by today's standards of sophisticated electronics. However, the same telephone system that transmits complicated computer signals, can also be used with a 50-year old telephone set. A thorough understanding of the basic electrical telephone, serves as a foundation for the study of more sophisticated communication systems.

The electronic telephone has circuitry that little resembles those circuits in the basic telephone. Even with its IC devices, however, the functions of the electronic telset are identical to those of its electrical counterpart. The real value of electronic telephones are their versatility in adding any number of service features to their operation. Phone number memories, recorders, intercoms, and other features are combined with the basic telephone circuitry to enhance the operation of these products.

Like the telset, the functional circuits of the central office are rather fundamental. The circuits can be functionally reduced to transformers, relays, and batteries. Again, however, the modern electronic central office utilizes the most sophisticated circuitry to emulate the functions of more basic components. For voice communication, the real value of electronics is not in function, but in speed. Electronics provides substantial cost benefits to the system.

The facilities of the central office provide for distribution of services to individual subscribers. This service is distributed through a pair of wires for each line. The wire-pairs are bundled into large cables that terminate at the central office's service area.

You should now have an understanding of the telephone system and its basic telephone services. You should also understand both the electrical and functional operation of the telset and the central office to which it connects.

SELF-TEST REVIEW

1. List the parts or designations for each of the wiring connections between the central office and telset.

   _____

   _____

   _____

   _____

   _____

2. Are single-line extension telephones connected in series or parallel with the tip and ring terminals of the telephone line?

   _____

3. What is the calculated loop current for each of three parallel connected telsets, if they are all simultaneously off-hook with a 48-VDC central office and 700 ohms loop resistance?

   _____

4. What is the ringer impedance of four parallel connected telsets that are on-hook, if the impedance of each ringer is 3k ohms and each is set for 30 Hz operation? _____

5. List the four insulator colors of 4-conductor station wire, and identify which two are primarily used for the tip and ring connections to the telephone line.

   _____

   _____

   _____

6. What is the calculated inductance (L) required for an LC bell ringer network that is resonant at 20 Hz, if the capacitor is 0.5 microfarad? _____

7. Identify the connection for each of the following terminals referenced in Figure 3-12.

A. _____

B. _____

C. _____

F. _____

G. _____

K. _____

R. _____

GN. _____

RR. _____

L1. _____

L2. _____

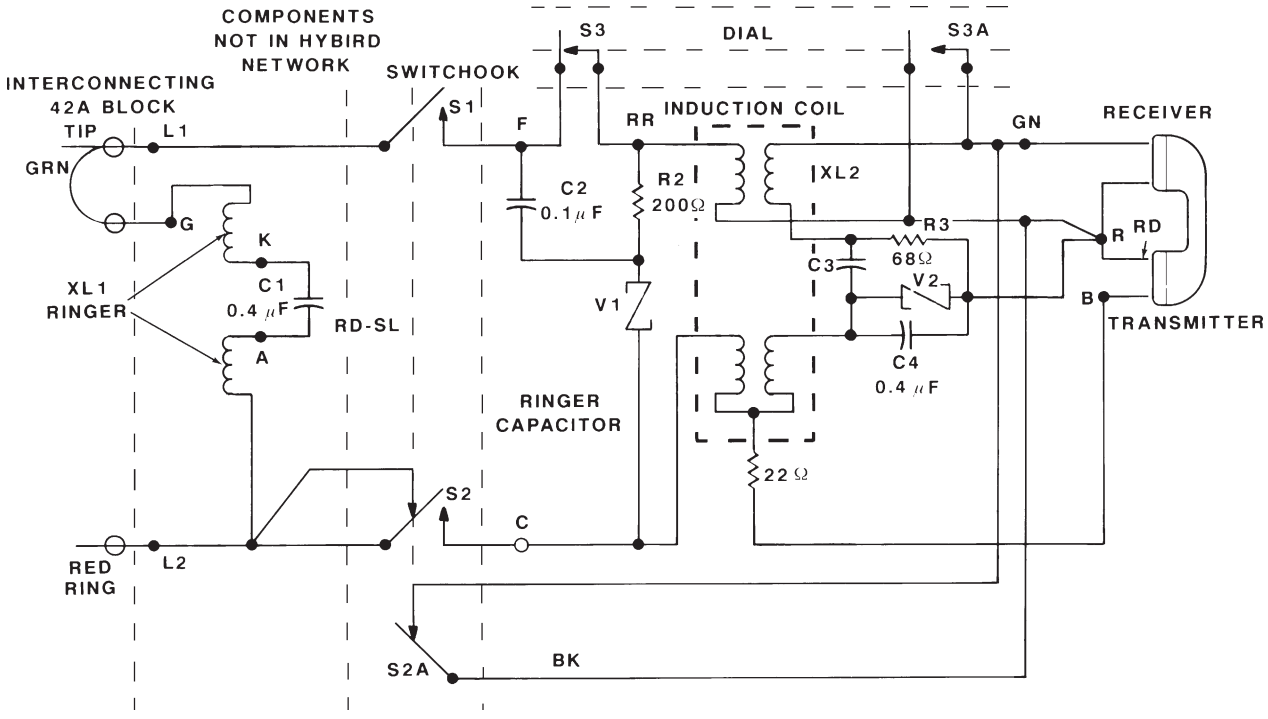


Figure 3-12

Figure for Questions 35, 36, 37.

8. What is the purpose of the varistors in the telset diagram in Figure 3-12, and how do they function? _____

_____

_____

_____

9. How do S3 and S3A in Figure 3-12 function to exclude the clicks from dialing being heard in the receiver? How does S2A prevent hookswitch clicks from being heard in the receiver? _____

_____

_____

_____

10. List the range of operating limits for the telset and local loop for the following specifications:

    A. Telset DC operating current. _____

    B. Local loop resistance. _____

    C. AC ringing signal voltage. _____

11. List all of the functional sections of a basic electronic telset.

_____

_____

_____

12. How does the power supply of the electronic telephone accommodate a reversal in the tip/ring voltage polarity, yet keep its internal polarity of + voltages the same? _____

_____

_____

_____

13. List the central office functions that are enabled by the loop relay:

_____

_____

_____

14. List the frequencies of the following central office signals:

    A. Dial tone. _____

    B. Busy. _____

    C. Ringback. _____

    D. Re-order. _____

    E. Telset off-hook. _____

15. Given two identical lines from a central office, which starting technique, loop start or ground start, will result in the higher loop current? Why? _____

    _____

    _____

16. Which side of the central office, lineside or trunkside, connects to the telset? _____

17. On which side of the central office, lineside or trunkside, is a 2/4-wire converter likely to be connected? _____

18. Describe three effects upon signals that fall under the classification of "signal conditioning."

    _____

    _____

    _____

19. What must be included in two-wire line amplifiers if they are to pass signals in two directions? Why?

    _____

    _____

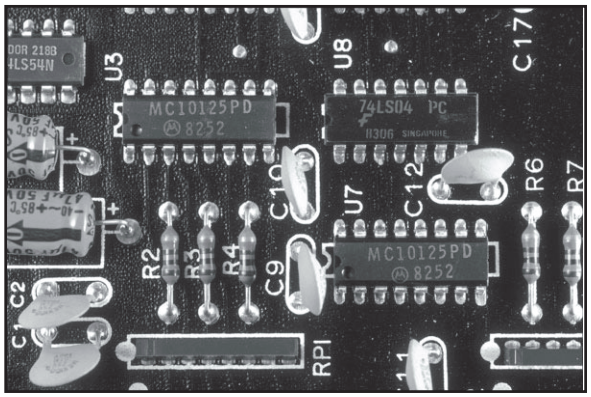
Section 2

Transmission Signals And Circuits

CHAPTER 4 — Generating and Detecting Signals

INTRODUCTION

In Chapters 1 through 3, we introduced the fundamentals of the telephone system. The emphasis was placed on basic single-line telephone service that is standardized for world-wide access. In this chapter, we introduce the fundamentals of signal generation, and circuits which are used to generate audio and voice frequency signals.



There are many electronic devices and circuits used to create electrical signals. Such circuits are collectively referred to as "signal generators" or "signal sources." More specifically, the circuits may also be classified as "oscillators" if they are digital circuits. Analog circuits and signals are continuous, like the sweep second-hand of an electric time clock. Digital circuits and signals are stepped, like the numerical time changes of a digital clock.

With both analog and digital classifications, the variety of generator circuits are far too numerous for detailed presentation in this text. To be consistent with our emphasis on signals, we will study only the fundamental techniques used to generate specific signals, and leave the detailed study of generator circuits to more specialized texts.

> Generators are circuits that create electrical signals. Oscillators generate analog signals, while multivibrators generate digital signals.

There are a variety of generator circuits used to create electrical signals in communication systems. Such signals are used extensively for signaling in communications. In the familiar telephone, for example, all of the tones, including the dial tone and the touch-tone digits, require generator circuits for their creation. Many other uses of generated signals were described in *The Principles of Electronic Communication* course, including how signals as carriers of modulation signals. You may recall that generator circuits are also used to create multiple frequencies (harmonic signals), and to convert signals from one frequency to another.

The lights, bells, and whistles that indicate the action or condition of a telephone circuit are "annunciators." The ringer of the telephone set is an annunciator that attracts your attention to respond to a phone call. For this action, it's your ears that detect (sense) the ring signal for your manual response. There are many detector circuits within the telephone system that do not require annunciators, as they electronically sense the presence of signals to control or trigger an automatic response. The dial switch of the central office is an example of such a detector that responds to the dial digits. Such detector circuits are used extensively by the central office to activate switching and signaling functions.

> Detector circuits sense signals within telephone systems and then trigger an annunciator, or provide for an automatic response to the signals.

The types of signal detectors are varied in proportion to the many distinct signals to which they respond. There are both digital and analog detector circuits, designed to respond to digital or analog signals. The detectors vary also by the distinct kinds of circuits or annunciators they drive. As with the generator circuits, we will not attempt to describe these circuits in detail in the context of this text. We will instead present only the fundamental techniques used to detect signals, and leave the detailed study of these electronic circuits to more specialized texts.

OBJECTIVES

When you complete this chapter, you will be able to:

- Identify the distinctions used to classify analog vs. digital techniques used in creating electrical signals.
- Describe the general operating characteristics of oscillator circuits used to generate sine wave signals.
- Describe the general operating characteristics of relaxation oscillator circuits used to generate ramp and sawtooth-waveform signals.
- Describe the general operating characteristics of multivibrator circuits used to generate triangle and squarewave signals.
- Describe the general operating characteristics of digital IC frequency generator circuits used to generate triangle and squarewave signals at frequencies divided down from a high-frequency clock oscillator.
- Identify and categorize the dominant analog and digital techniques used for electrical signal detection and driving common annunciators.
- Classify the characteristics of signals to which detector circuits are applied, including the presence of signals, frequency and phase discrimination, triggering power levels, and triggering from time periods.

CREATING SIGNALS

Earlier in this course we focused upon the use of specific "signaling" signals (not voice signals) used for the operation of telephone services. Other signals, called "test tones," are also used in communications equipment for measuring circuit performance. Like voice signals, the signaling signals and test tones have specific power levels, frequencies, and waveforms. Unlike voice signals, however, these signals are created electronically, not acoustically. The circuits used to electronically generate these signals are the focus of this chapter.

> The signaling signals and test tones used in telephone systems are created electronically.

There are two distinct circuit techniques used to generate signal waveforms. These are classified as analog and digital techniques. The analog techniques use oscillator circuits to produce sine waveforms. These waveforms result from a continuous shift in signal phase. The digital techniques use switching multivibrator circuits to produce square, triangle, or ramp waveforms that result from abrupt shifts in signal phase.

Oscillators

Under certain conditions, amplifier circuits can produce output signals even when no deliberate input signals are applied to them for amplification. This phenomenon, called "regeneration," occurs when there is some signal path back from an amplifier's output terminal to its input terminal.

The loop around the amplifier provides this regeneration and creates output signals from its circuitry. An amplifier that is intentionally configured with a feedback loop to create output signals is called an "oscillator." Oscillators have output terminals, and no external input terminals. Their inputs are coupled to their output terminals with a feedback loop network in order to generate signals, as shown in Figure 4-1.

> An amplifier that is intentionally configured with a feedback loop to create output signals by regeneration, is called an "oscillator."

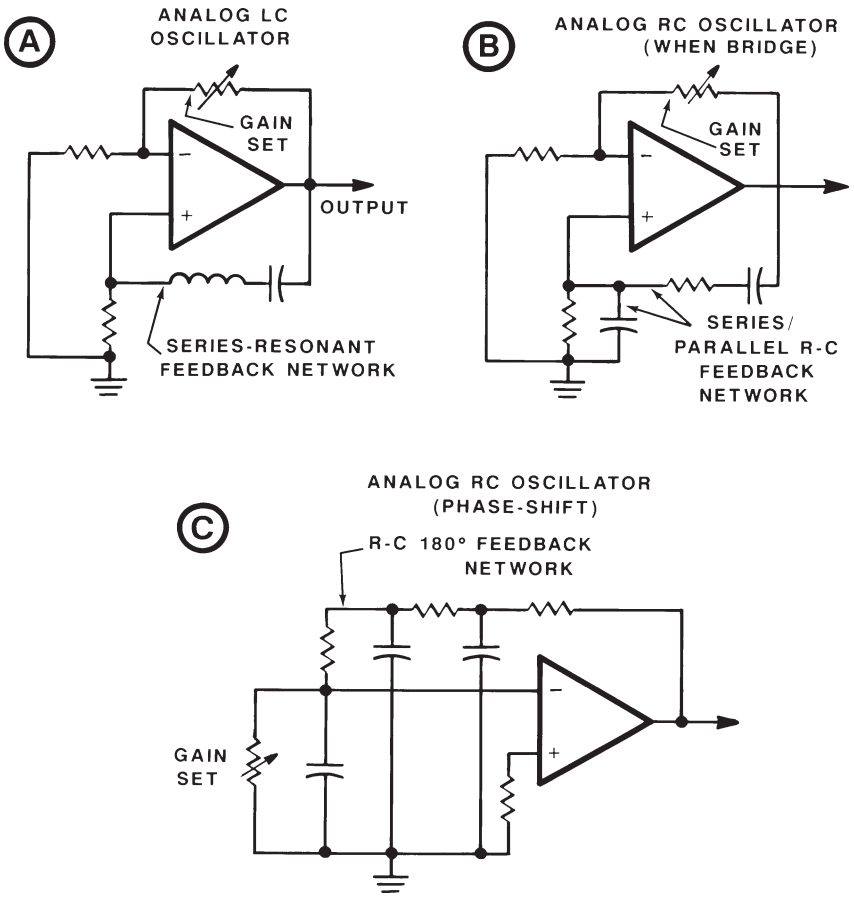


Figure 4-1

Analog oscillators.

There are two criteria required for oscillation in an analog amplifier circuit. The first criterion is that the level of the feedback signal is inversely proportional to the gain of the amplifier. An amplifier with a gain of 50 must feedback 1/50th of its output signal to its input. The second criterion is that the phase of the feedback signal be positive, or in-phase, at the frequency of oscillation. The signal phase at the input of a non-inverting amplifier is 0°, while the signal phase at the input of an inverting amplifier is 180°. The phase shift of the feedback signals must be equal to these phase shifts.

> For oscillation, the level of the feedback signal must be inversely proportional to circuit gain, and the phase of the feedback signal must be positive.

Figure 4-1A shows a simplified circuit that functionally represents the operation of an analog oscillator. This amplifier, for example, has a gain of 20. Therefore, it requires that 5% (one twentieth) of its output signal be applied (fed back) to its input. For phase factors, we can use the example of a series-resonant LC network, as shown in Figure 4-1A. The phase shift of this network is 0° only at its resonant frequency. For that reason, the oscillator will generate output waveforms at the resonant frequency of this LC network. The oscillator circuit for generating DTMF signals, in Figure 2-10A of Chapter 2, uses resonant LC networks. The phase shift of this LC network is 180° because it is applied to its inverting amplifier connection.

LC networks are used extensively in traditional telephone circuits. In electronic circuits, however, inductors are seldom used for generating audio frequency signals. Audio-frequency inductors are generally bulky and heavy, and they are more costly than alternative circuit techniques for obtaining frequency-selective phase shifts. In almost all modern audio frequency oscillator designs, it is preferable to use RC (resistance capacitance) networks for frequency-selective phase shifts. RC networks are easily configured to provide either a 0° or a 180° phase shift at a specific frequency. Figures 4-1B and 4-1C show two representative basic RC oscillator circuits with 0° and 180° phase shifts respectively.

Relaxation Oscillators

There is another popular technique for producing signal waveforms with RC components. This technique does not rely upon feedback phase shift, but rather, upon the RC time constant of charging a capacitor. The resulting rate of voltage change in an RC network connected to an amplifier generates signal waveforms at specific frequencies. In relaxation oscillators, a capacitor is connected to an electronic component that alternately allows the capacitor to charge and discharge. The capacitor voltage rises until the component saturates and discharges it; then the charging process repeats itself, which results in oscillation. As the electronic component is saturated, the relaxation oscillator behaves more like a digital circuit than an analog circuit.

> A relaxation oscillator uses a charging capacitor connected to a component that saturates at a specific voltage level and discharges the capacitor.

Figure 4-2A shows a simple RC network connected to a zener diode. The diode "saturates" at its breakdown voltage, and discharges the capacitor. The charge on the capacitor again builds until it reaches zener breakdown, and the process repeats itself. The frequency of oscillation of this circuit is inversely proportional to the RC time constant of the circuit, and the ratio of the applied and zener voltages. The output waveform of this circuit is a ramp or "sawtooth."

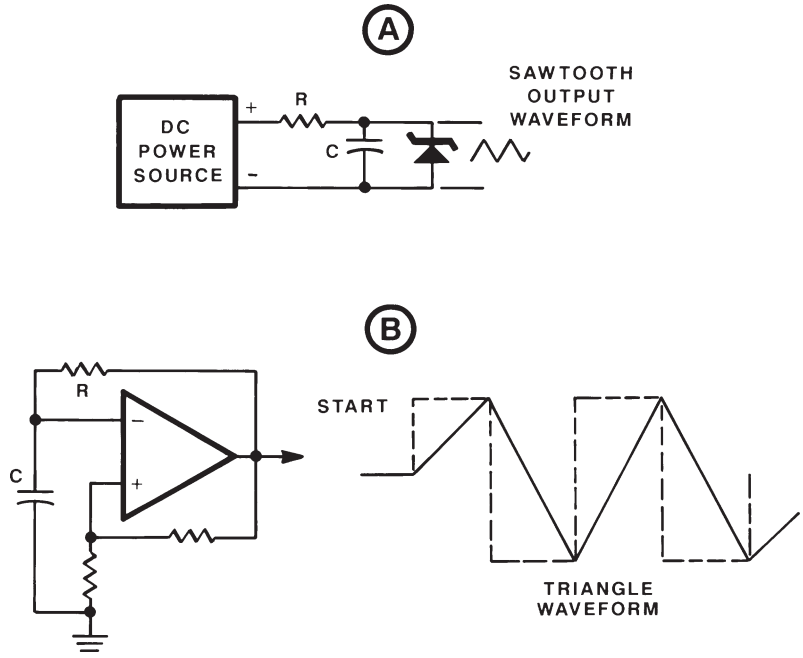


Figure 4-2

Relaxation oscillators.

Figure 4-2B shows the RC network connected in the feedback loop of an IC amplifier. The loop is from the amplifier's output to its non-inverting input. The source of charging voltage is the amplifier's output voltage. As the capacitor charges toward positive, it drives the amplifier's output negative; it's an inverting amplifier. When saturation is reached in this circuit, the polarity of the feedback is opposite to the first charge of the capacitor. The result is recharging the capacitor in the direction of opposite polarity. The process then repeats itself, generating a triangle output waveform.

Multivibrators

The more popular digital technique used for generating signals is with circuits called "multivibrators." Like relaxation oscillators, multivibrators rely upon amplifier saturation and charging capacitors in RC networks. Unlike relaxation oscillators, however, multivibrators use two stages of amplification, with each switching between opposite limits of saturation. This switching action classifies multivibrators as true digital circuits.

> Multivibrators use two amplifier stages that alternately switch between their opposite limits of saturation.

The two amplifiers in the multivibrator can be likened to a "see-saw," as when one amplifier is at its positive limit, the other is at its negative limit, and when they switch, each amplifier assumes the opposite condition of the other. This circuit is sometimes called a "flip-flop."

Figure 4-3A is a simplified multivibrator circuit using two amplifier stages. Figure 4-3B shows the signal waveforms that are available at each of the critical points of the circuit. The capacitor in the feedback loop of amplifier two determines the charging time and frequency of the output waveform. Each of the amplifiers have resistive feedback loops to the same non-inverting input of amplifier one.

The switching action of the multivibrator starts with the output of amplifier two at a saturated limit of its operation (negative). This output voltage charges the capacitor to oppositely saturate this amplifier, which causes it to switch to its opposite limit (positive). The output of amplifier two also loops back to the non-inverting input of amplifier one, to drive this amplifier's output positive at the other side of the capacitor. The result is a triangle waveform at the output of amplifier one, and a square waveform at the output of amplifier two.

Multivibrators take many forms in addition to that described here. In current use, they are available as specialized IC waveform generators designed for specific applications. The DTMF tone generator in most electronic telephones, for example, is available as a single device that

produces 16 accurate frequencies. The advantages of the digital, square-wave output of these multivibrators include their stability and frequency accuracy. More importantly, however, square-wave signals can be easily and accurately frequency divided.

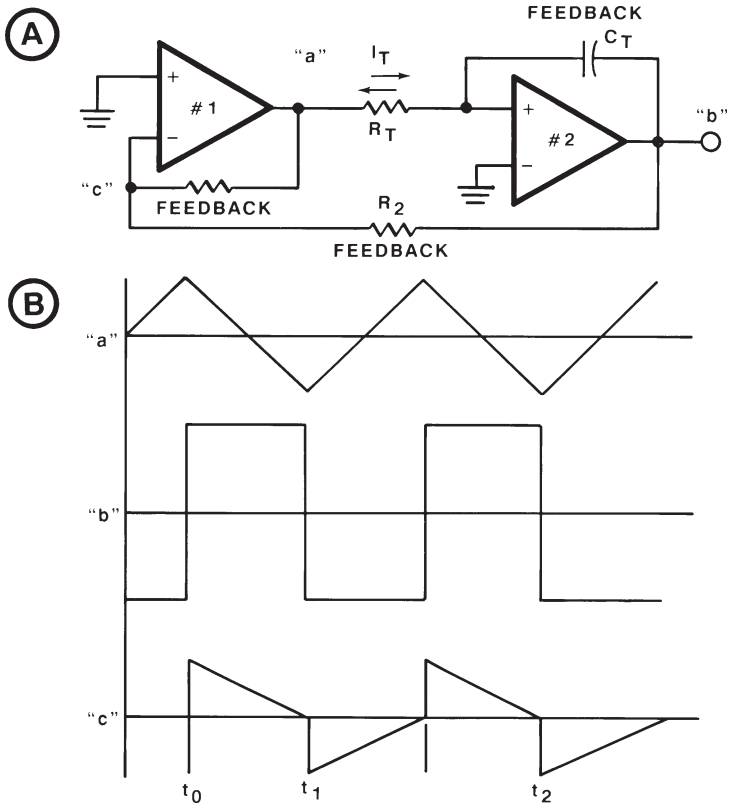


Figure 4-3
Multivibrator.

Digital IC frequency generators are widely used in communication systems. They produce square-wave signals that can accurately be frequency divided.

Figure 4-4 is the diagram for a typical DTMF generator that produces its 16 frequencies by dividing down square-wave signals from a single-frequency oscillator. The entire circuitry in the Figure is included in a single IC chip. All of the internal signals are square waves for precise frequency division functions, with the final "waveform shaper" circuits used to convert the square waves to sine waves.

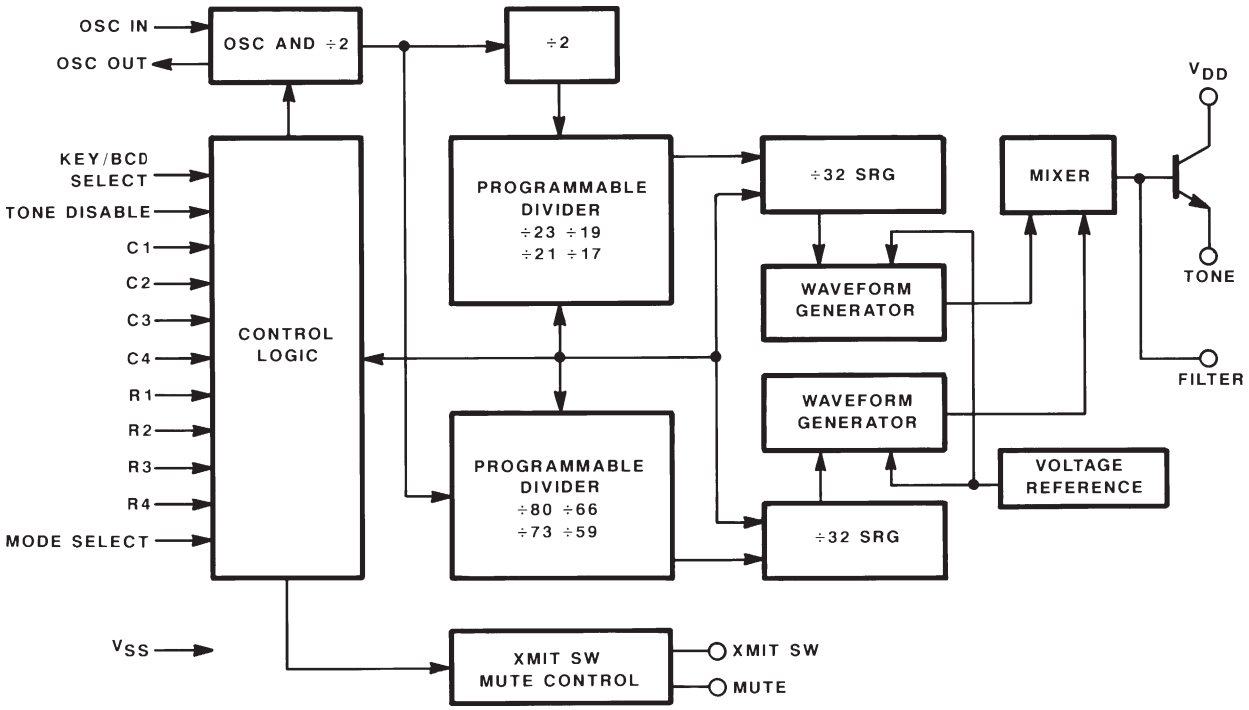


Figure 4-4

DTMF frequency divider.

As with the DTMF IC of Figure 4-4, waveform generators often use piezoelectric crystals to assure precise operating frequencies. These crystals vibrate at an exact frequency, with properties equivalent to electrical resonant LC networks. Oscillators and multivibrators that use crystals in this way are often identified as "crystal stabilized frequency generators."

Stabilized oscillators and multivibrators are intended for precise single-frequency operation. Single-frequency (SF) signaling is used extensively in telephone systems. However, there are also many communication system functions that require signal generators to operate over a range of frequencies. These circuits are classified as "tunable" generators, with their operating frequencies set either manually or

electronically. Most electronically-tuned generators are called "voltage-tuned oscillators" (VTO) or "voltage-controlled oscillators" (VCO). These oscillators are often used to "sweep" test a communication circuit's frequency response.

DETECTING SIGNALS

You may recall that many of the signals used in telephone systems (such as advisory signals) are detected by the ear of the calling or called parties. Other signals (such as DTMF signals) are detected by the ear, but also, by an electronic circuit that triggers an action in the telephone system. Still other signals (such as out-of-band signals) are not detected by the ear, but trigger an action in the telephone system. With the advent of automation, telephone services utilize an extensive number of signals that trigger the functions of their operations. The circuits and components that determine whether these signals are present are called "detectors."

> The circuits and components that automatically determine whether signals are present in communication systems are called "detectors."

Relays are the simplest detectors. A relay engages when current flows through its coil. A relay is used to "detect" an off-hook condition at the terminal equipment on the local loop. Once the loop current is detected, the other functions of telephone service can proceed. The detector, therefore, also enables the operation of system functions.

Detecting more complicated signals with specific frequency, power, and time dimensions requires electronic circuits that are also more complicated than a simple relay. However, even the most complicated of these circuits perform the same purpose as a relay; they detect signals and enable or disable system functions. We'll describe some of these signal detector circuits in the following paragraphs.

> The purpose of detectors is to determine whether specific signals are present, and enable system functions that relate to those signals.

Detecting Frequency

A prime example of circuits that detect precise signal frequencies are those used in the DTMF decoder. Errors in this function cannot be tolerated, as they will result in incorrect numbers being dialed. The basic building block circuit of the DTMF decoder, and of other precise frequency detectors, is the phase-locked loop (PLL). Figure 4-5 is the block-function and general schematic diagram of a PLL circuit used for detecting a single-frequency signal.

Figure 4-5A shows the general structure of the PLL circuit. In its operation, two signals are applied to its phase detector. If the two signals are not identical in frequency, there is an output voltage shift from the detector block. This voltage is applied to a low-pass filter to ensure the circuit responds only to slower changes in detector output voltages. The output of the filter is applied to an amplifier to increase the filter's output voltage level, and to isolate the filter from external loading effects. The output of the amplifier also loops back to a voltage-controlled oscillator (VCO) to control its frequency. The output of the VCO is one of the input signals applied to the phase detector.

When the PLL is connected in this manner, the output voltage from the amplifier causes the VCO to shift frequency until it matches that of the other input signal applied to the phase detector. When the two frequencies are identical, there is a zero output voltage from the detector, and the VCO remains at its current operating frequency. By this process, the VCO is locked to the frequency of the other applied input signal.

Figure 4-5B is the generalized schematic diagram of the phase detector. It is configured as a differential amplifier, which rejects common-mode signals. These circuits have an output voltage if their input signals are not identical, and they have zero output voltage only when their input signals are identical. To provide a greater sensitivity, this phase detector uses three interconnected diff-amp circuits.

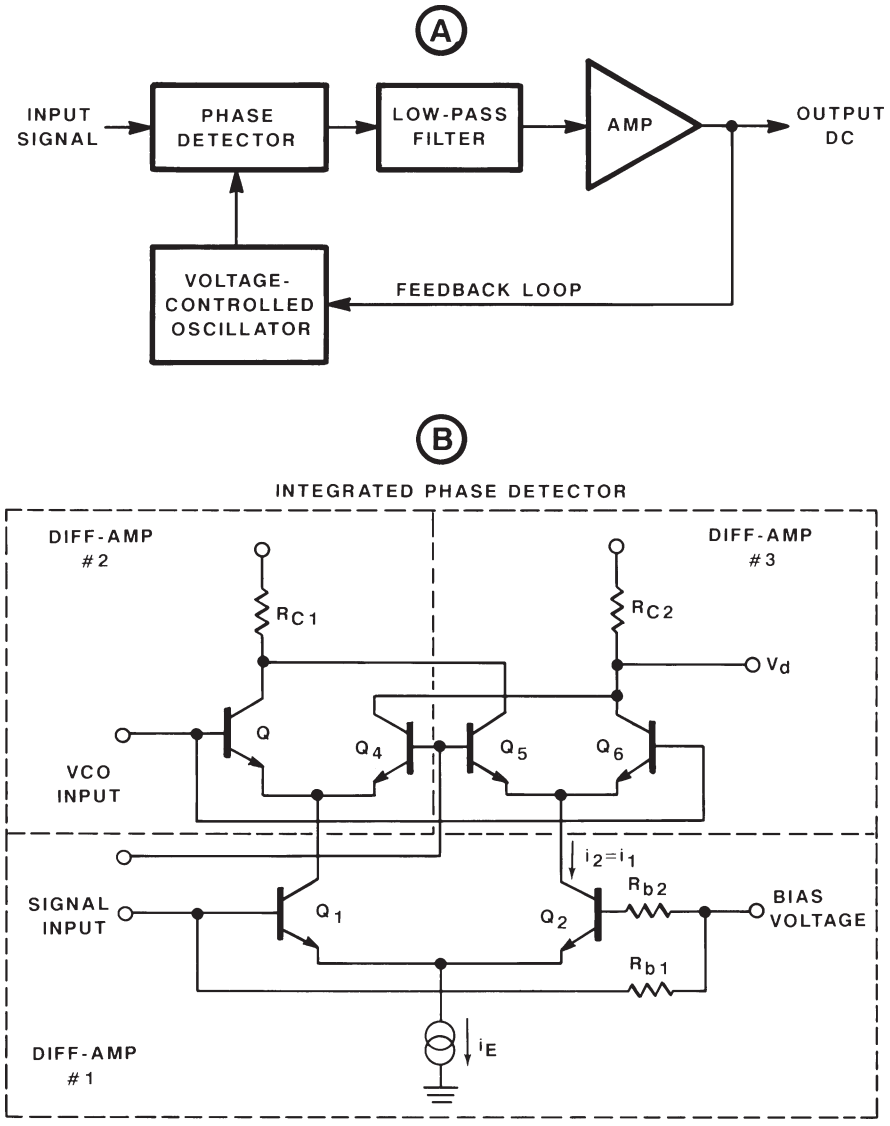


Figure 4-5

Phase-locked loop detector.

The phase-locked loop can be used to detect frequencies when it is connected as a tone decoder. Figure 4-6A shows how a PLL is used for this purpose. For operation, a reference frequency is first established with a basic RC network connected into the VCO. The applied signal is connected to the phase detector for comparison with the VCO signal frequency. The amplifier output of the PLL shifts to zero only when (or if) the applied signal and the reference VCO signal are identical.

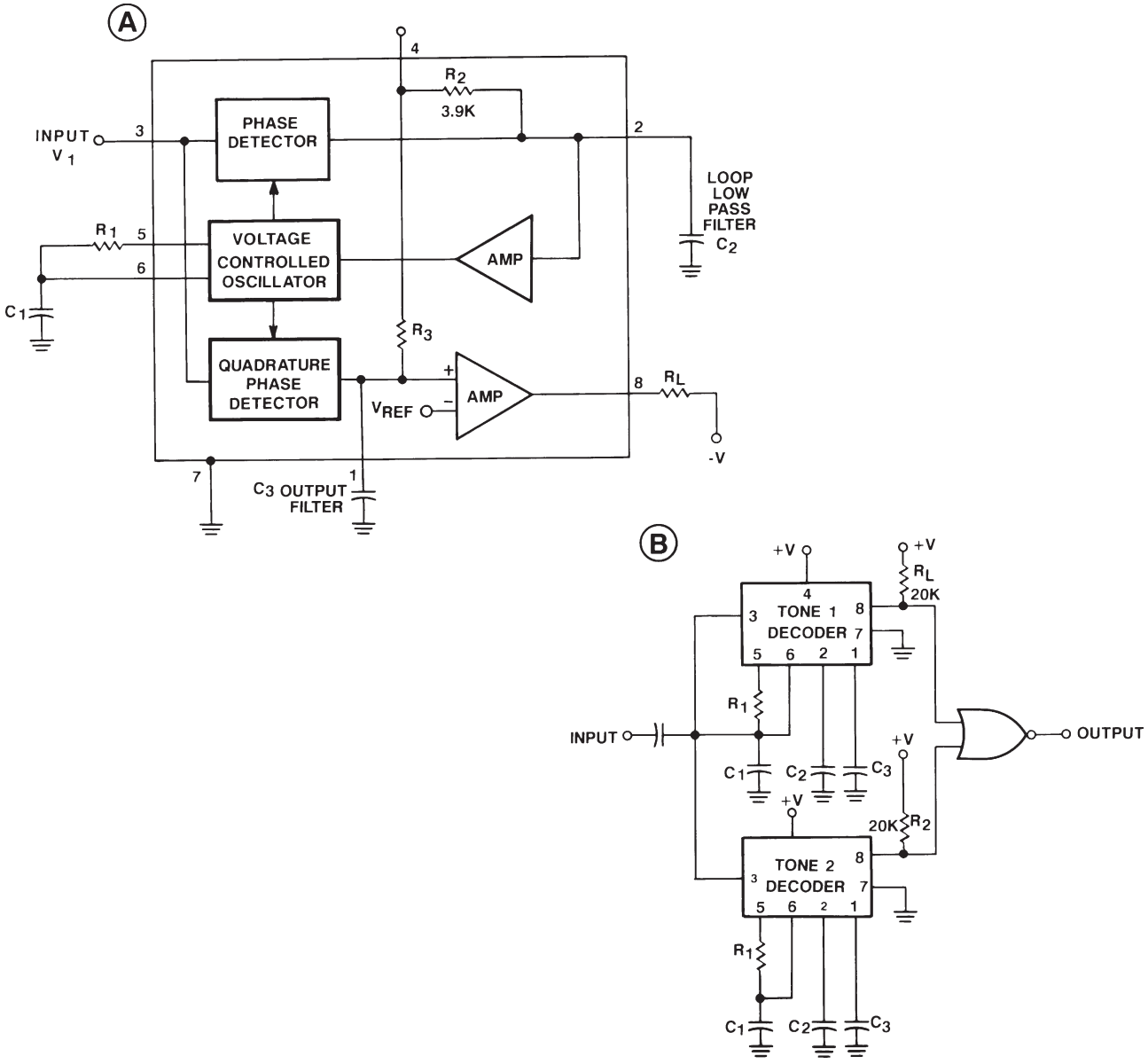


Figure 4-6

PLL tone decoder.

Figure 4-6B shows two PLL circuits connected to detect two simultaneous frequencies, such as used in DTMF dialing. Each of the PLLs is tuned to one of the DTMF frequencies, such as 697 and 1209 Hz, respectively, which are equal to DTMF dial digit #1. The outputs of both of these PLLs drive a NOR gate. When both inputs to the NOR gate are low (zero voltage outputs from the PLLs), the gate's output is high, and indicates that the two frequencies are present. Connecting eight such PLL circuits in this way provide complete eight-frequency decoding of DTMF signals. DTMF decoders of this type are available within a single IC chip.

As with DTMF decoding, almost all of the frequency-based signaling signals in telephone systems can be detected with PLL tone decoders. Similar decoder IC devices are available for the wide range of signals used in telecommunications systems. While frequencies can be detected with more-conventional LC resonant circuits, the PLL is the most practical and precise method currently available.

Detecting Power Levels

Very often, the power level of DC and other signals must be determined to assure the proper operation of a communications system. In the local loop of a telephone circuit, for example, there must be a minimum of 20 mA and a maximum of 120 mA of DC loop current with the telset off hook. If the current values exceed these limits, an alarm at the CO indicates a malfunction. Most power detectors are actually voltage detectors that are designed to indicate the level of a DC or AC signaling signal across a known resistance or impedance. The detectors can be configured to indicate either under-voltage or over-voltage conditions.

> Power detectors are designed to indicate the voltage level of DC or AC signaling across a known resistance or impedance.

The most precise means of detecting voltage levels is with an IC device called a "comparator." The comparator is simply a differential input operational amplifier with high gain. Like a digital IC, the high gain of this IC drives its output to saturation. Figure 4-7A shows the basic connection of the comparator. In operation, a reference voltage, equal to the limit to detect (signal limit), is set at the amplifier's inverting input. The voltage level of the signal under test is applied to the non-inverting input of the amplifier. When the signal under test is less than the reference voltage, the amplifier's output is saturated at one polarity, and if the signal rises above the reference voltage, the amplifier's output switches to saturation at the opposite polarity.

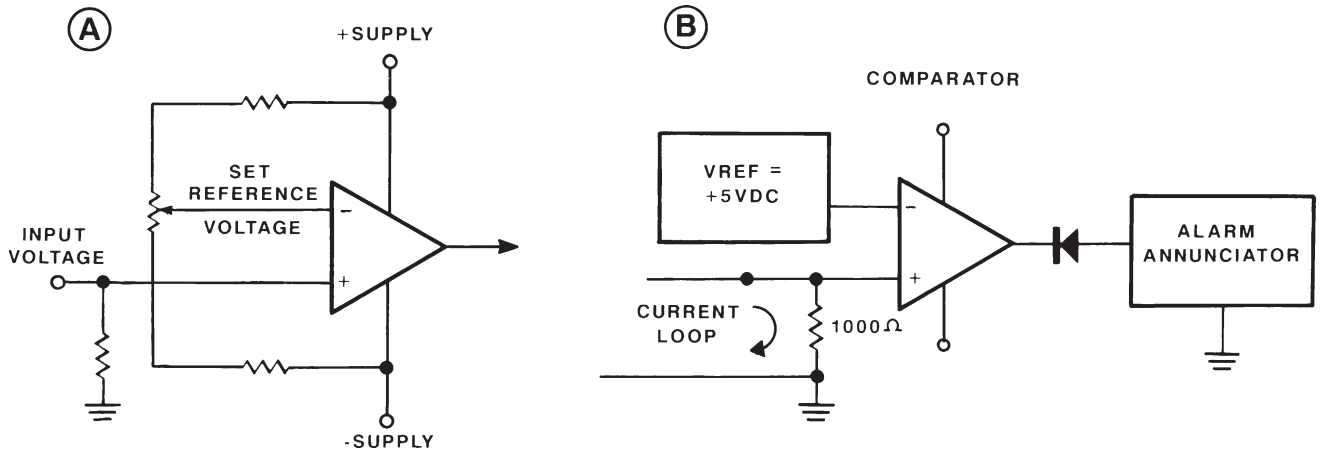


Figure 4-7

Voltage comparator.

Figure 4-7B shows an example of a comparator used to detect, and trigger an alarm if more than 5 mA (DC) of current flows in a circuit. A 1k-ohm resistor is placed in the loop of current flow, with one side connected to the comparator's test signal (non-inverting) input. A current flow of 5 mA yields 5 VDC across the 1k-ohm resistor.

To set this alarm level, a voltage source of 5 VDC is connected to the reference (inverting) input of the comparator. With less than 5 mA flowing through the loop, the output of the comparator is saturated at $-V_{EE}$. If the loop current exceeds 5 mA, however, the voltage at the test signal input of the comparator exceeds the reference. Once the test signal exceeds the reference, the output of the comparator switches to saturation at $+V_{CC}$. The positive voltage at the comparator's output triggers the alarm.

Comparators are also used to detect the level of AC signaling signals. There are two techniques used for this function. Figure 4-8A shows a comparator that is set to trigger when the peak value of an AC waveform exceeds the DC reference voltage. Figure 4-8B shows a rectifier and filter network connected as a peak voltage detector at the comparator's test signal input. This network converts the AC signal to a DC level equivalent to its peak voltage. The DC reference voltage is set to the maximum level of the peak voltage detector.

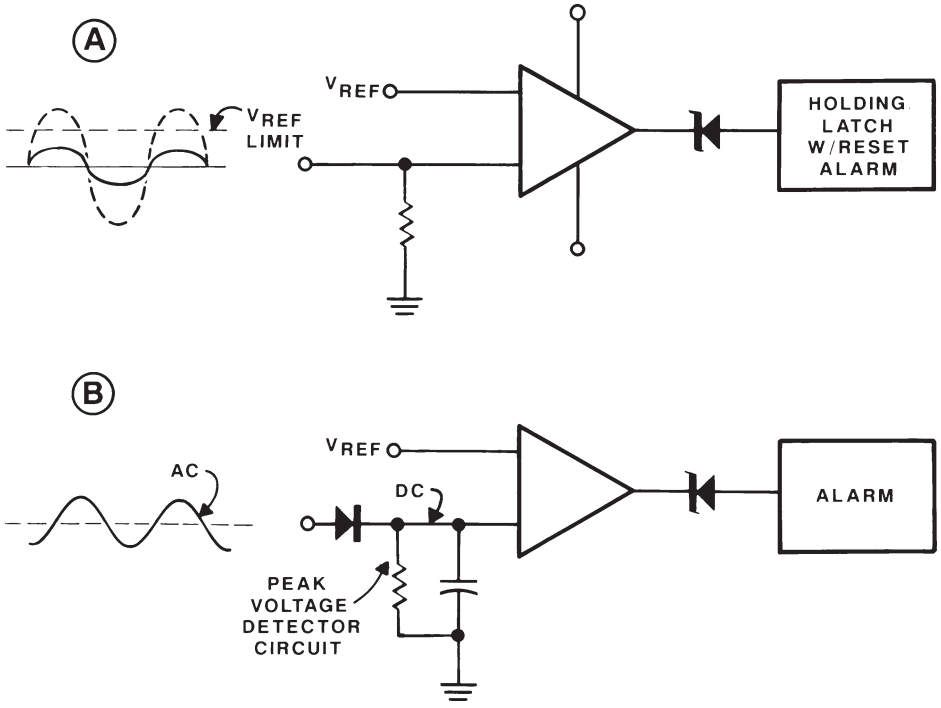


Figure 4-8
Signal level detectors.

Time Detection

While various frequency signals are used extensively for signaling functions in communications systems, there are also some signals that vary in time. With the telephone time-out functions described in Chapter 1, for example, inactivity for a specific time interval triggers an advisory message to the caller. Timing circuits are available to detect these time intervals. In older telephone systems, timing was accomplished with mechanical and electromechanical components. In modern communications systems, these timing circuits take the form of specially designed IC devices called "timers."

IC timers use the basic time-constant DC charging characteristics of RC networks, along with amplifiers connected as comparators that operate in saturation. Figure 4-9 is the general schematic diagram of a typical IC timer. The RC timing network is connected to the noninverting input of the comparator. The reference voltage for the comparator is obtained from the voltage divider network of two series resistors. A single-transistor trigger connects across the capacitor.

IC timers include time-constant DC charging RC networks, along with voltage comparator amplifiers.

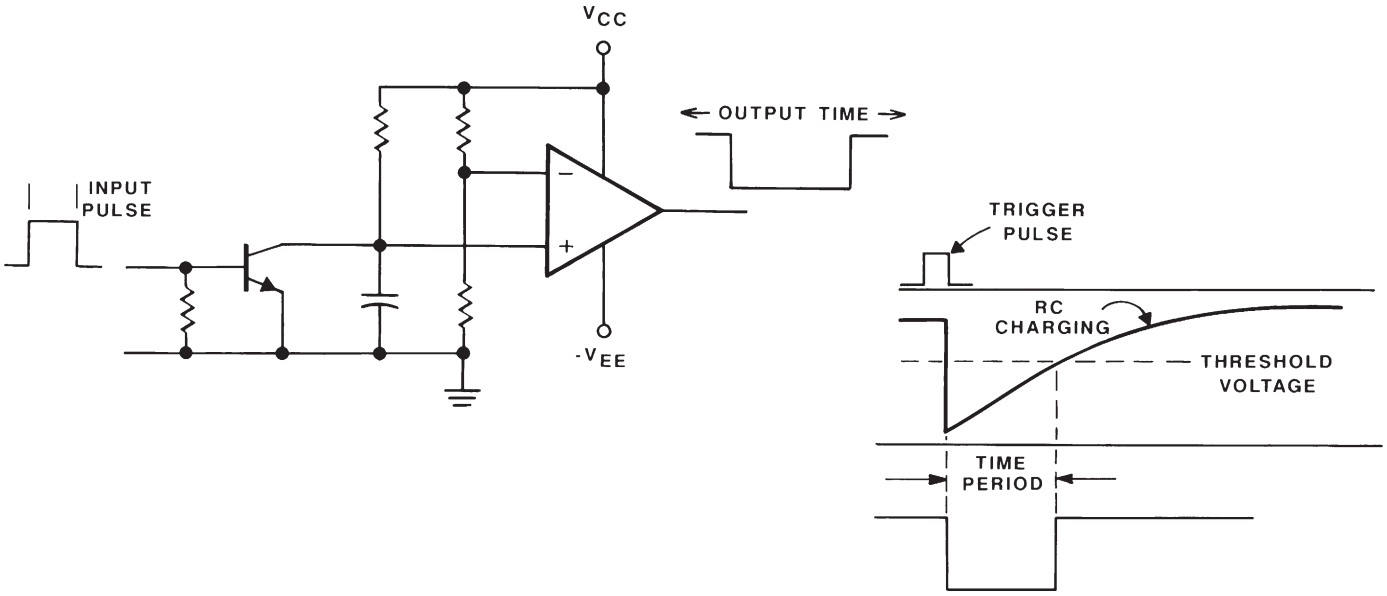


Figure 4-9
IC timer circuit.

The timing period begins when a positive voltage pulse is applied to the transistor trigger. The transistor momentarily saturates, to discharge the capacitor, and begin its RC charging cycle. When the capacitor charges to the level of the reference voltage at the comparator's inverting input, the output of the comparator saturates at $+V_{CC}$. With the application of the trigger pulse, the output of the comparator saturates to $-V_{EE}$ and remains at that negative voltage for the duration of the timing period.

SUMMARY

In this chapter, we identified the circuits which are used to generate telecommunications signals: sine-wave oscillators, relaxation oscillators, and multivibrators. The sine-wave circuits are classified as linear circuits, because their voltage and currents are continuously changing to develope the smooth sine waveforms. Relaxation oscillators discharge the voltage stored in charging capacitors within their circuitry. The fundamental waveform produced by a relaxation oscillator is the ramp or sawtooth.

The multivibrators are classified as switching circuits because they use electronic switches in tandem to alternately charge and discharge the voltage stored in charging capacitors within their circuitry. The multivibrators produce square and triangle waveforms at their outputs. The major advantage of these circuits is their ability to generate square waveforms. The frequency of square-wave signals can be accurately divided to obtain many stable frequencies from a single oscillator. This approach is used extensively in communication circuits.

The DC, sine-wave, sawtooth, triangle, and square-wave signals produced within these circuits are used as signals to manage the operation of communication services. Once the signals are generated, they must be detected to identify which operational function they indicate. The detectors are designed to discriminate the following:

- Presence of absence of signal power.
- Signal frequency.
- Signal phase
- Signal level.
- Signal timing.

Once detected, the signals trigger a circuit function, or annunciator, that informs the listener, or system, that the signal is present.

SELF-TEST REVIEW

1. Which telephone system signals are created electronically with oscillator circuits?

   A. Messages.
   B. Voice Signals.
   C. SF Signals.
   D. DC Signals.

2. Which circuit is more likely to produce a square-wave signal?

   A. LC oscillator.
   B. Relaxation oscillator.
   C. Multivibrator.
   D. Comparator.

3. What are the two criteria required to assure that oscillation will occur when you use an amplifier circuit?

   _____

4. For oscillation, at what phase angle must the feedback signal be applied to an amplifier's inverting input?

   A. 0°
   B. 90°
   C. 180°
   D. 270°

5. What phase shift will a series LC feedback circuit have at its resonant frequency?

   A. 0°
   B. 90°
   C. 180°
   D. 270°

6. Across which component of a simple RC relaxation oscillator will the voltage increase with time? _____

   _____

7. What is the typical waveform output from a simple RC relaxation oscillator?

   A. Sine wave.
   B. Square wave.
   C. Triangle wave.
   D. Sawtooth wave.

8. What is the typical waveform output from a simple analog RC oscillator?

   A. Sine wave.
   B. Square wave.
   C. Triangle wave.
   D. Sawtooth wave.

9. Which output waveform cannot be obtained from a multivibrator?

   A. Sine wave.
   B. Square wave.
   C. Triangle wave.
   D. Sawtooth wave.

10. What is the major advantage of using multivibrators rather than analog oscillators to generate signals? _____

    _____

    _____

11. Which dimension of DTMF signals is the most critical to detect?

    A. Frequency.
    B. Power.
    C. Current.
    D. Time.

12. Which telephone signal is detected by the loop relay?

    A. Frequency.
    B. Power.
    C. Current.
    D. Time.

13. List the functional blocks of the PLL. _____

    _____

    _____

14. If two signals of identical frequency are applied to the phase detector, the detector's output voltage will be:

    A. zero.
    B. saturated negative.
    C. saturated positive.
    D. proportional to applied signal voltages.

15. How are the reference frequencies set for a PLL that is to be used as a tone decoder? _____

    _____

16. What component is driven by the dual DTMF tone decoders to detect the frequency pairs for each of the dial digits?

    A. Differential amplifier.
    B. Comparator.
    C. Digital flip-flop.
    D. Digital NOR gate.

17. What component is often used to accurately detect voltage levels in communication systems?

    A. Differential amplifier.
    B. Comparator.
    C. Digital flip-flop.
    D. Digital NOR gate.

18. With a reference of +5 VDC on the inverting input of a comparator, and a test signal of +2 VDC on the non-inverting input of the comparator, what is the voltage level of the comparator's output?

    A. Zero.
    B. Saturated negative.
    C. Saturated positive.
    D. Proportional to applied signal voltages.

19. Which component is used within the IC timer to obtain precise switching times from a charging capacitor?

    A. Differential amplifier.
    B. Comparator.
    C. Digital flip-flop.
    D. Digital nand gate.

CHAPTER 5 — Transmission Lines

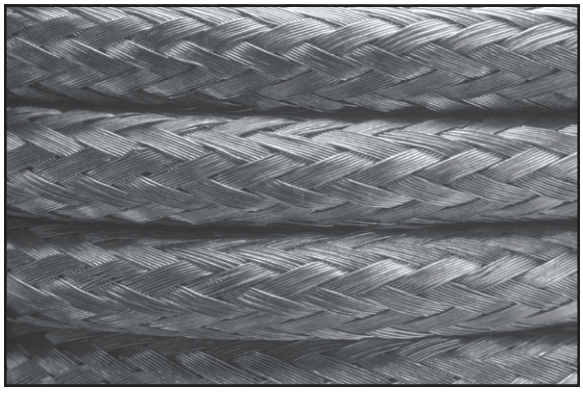
INTRODUCTION

The word "telecommunication" describes a way of making immediate communication at a distance. To make communication at a distance requires some means of transmitting information, and the option of obtaining an immediate reply. "Transmission" is the word used to describe the way that signals pass from one point to another along a communication path. With current technology, the information is most efficiently transmitted using wires, copper cables, radio waves, microwaves, satellites, and fiber optic cables.

> Telecommunication involves information transmitted via media such as wires, cables, radio, microwave, satellites, and fiber optics.

In this chapter we will focus upon the electrical properties and performance of copper wires and cables as used in transmitting audio and telephone signals. Copper wires and cables are prominent media for communicating audio and telephone signals, and they are fundamental to the study of other transmission media.

The wires that are used to transmit signals are called "transmission lines," and the circuits that often include the wires through which the signals pass are called "transmission circuits." A large combination of transmission circuits is called a "transmission network." The Public Telephone Network (PTN), for example, is a transmission network.



Transmission is the word used to describe the way signals pass from one point to another along a communication path.

The objective of the transmission process is to get signals from one point to another with the least amount of power loss or distortion. An ideal transmission circuit provides for accurate output reproduction of signals that closely resemble their input waveforms. To reach this objective, the electrical properties of transmission circuits must be measured, and then compensated, for optimum performance.

OBJECTIVES

When you complete this chapter, you will be able to:

- Specify and calculate the electrical properties of transmission lines in units of R, L, and C, from their geometry and insulation materials.
- Specify and calculate the electrical properties upon a transmission line's characteristic impedance.
- Determine the effects of line impedance upon the transfer of signal power and frequency response characteristics of transmission lines.
- Apply the concepts of phase shift due to the LC properties of transmission lines, to the velocity of signals moving along the lines.
- Describe and calculate the velocity factor of signals moving along transmission lines.
- Describe the non-linearities of R, L, and the velocity of signals in transmission lines due to skin effect.
- Describe the structure and advantages of coaxial cable, and calculate its electrical properties from specifications of its geometry and insulation material.

ELECTRICAL PROPERTIES OF LINES AND CIRCUITS

Transmission lines and circuits are comprised primarily of formed wire pairs, separated by insulation. These lines have predictable and measurable electrical properties that affect communication signals passing through them. The electrical properties are the same as those you studied when you learned basic electrical principle. They are resistance (R), capacitance (C), and inductance (L). Electrical transmission lines are the equivalent of RCL networks.

> Transmission lines are electrical networks that comprise the combined basic circuit elements of resistance, capacitance, and inductance.

Resistance

We can examine the electrical properties of transmission lines by looking at a simple parallel pair of wires, as shown in Figure 5-1A. The wires are electrical conductors. Their resistance is low, as they are made of copper, but with small diameters and long lengths, the resistance accumulates along the lines. Figure 5-1B shows the true electrical representation of a wire's resistance, distributed along its length. The resistance of a reference length of copper wire depends upon its diameter. The total resistance of the wire is directly proportional to its length, and inversely proportional to its diameter. Recall that the higher gauge numbers indicate smaller wire diameters.

> The electrical resistance of a wire is directly proportional to its length, and inversely proportional to its diameter.

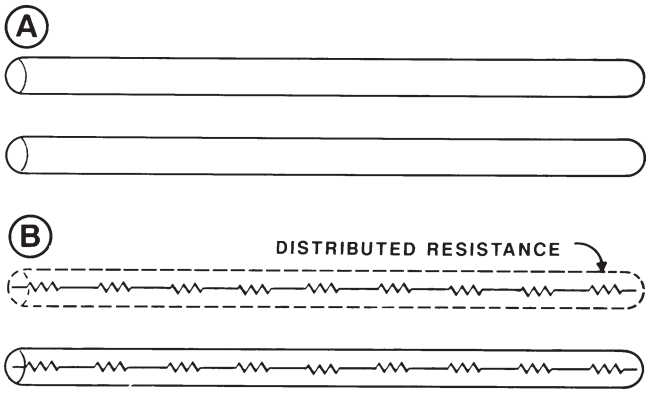


Figure 5-1

Distributed resistance.

Table 5-1 lists the diameter vs. resistance of copper wires from gauge 16 through gauge 26. These are the popular diameters used in telephone service. 22-gauge wire is the more popular in local loop service applications. Its resistance is about 16 milliohms-per-foot. Since there are two wires in a wire pair, the resistance of the 2-wire line is about 32 milliohms-per-foot, 32 ohms per-1000 feet, and 170 ohms-per-mile.

Table 5-1

Wire diameter and resistance.

WIRE DIAMETER AND RESISTANCE (COPPER)

Gauge (AWG or B&S)	Diameter (in.)	Resistance (Ω/1000 ft)	Gauge (AWG or B&S)	Diameter (in.)	Resistance (Ω/1000 ft)
16	.05082	4.016	22	.02535	16.14
17	.04526	5.064	23	.02257	20.36
18	.04030	6.385	24	.02010	25.67
19	.03589	8.051	25	.01790	32.37
20	.03196	10.15	26	.01594	40.81
21	.02846	12.80			

This data, along with the information in Chapters 1 and 2 about the local loop and telset, makes it is possible to quickly calculate the loop current for a 10-mile circuit. The 48-volt talk battery current from the CO will be limited by 1700 ohms of series loop resistance (10 miles × 170 ohms/mile) plus about 200 ohms of telset resistance. The loop current is calculated as follows:

$$I_{LOOP} = \frac{V}{R_{TOTAL}} = \frac{48}{(1700 + 200)} = 25\ MA$$

It is also practical to calculate the maximum loop length for a 20 mA minimum telset current, with a 22-gauge line pair, as follows:

$$R_{TOTAL} = \frac{V}{I_{LOOP}} = \frac{48}{.02} = 2400\ \Omega$$

$$R_{LINE} = R_{TOTAL} - R_{TELSET} = 2400 - 200 = 2200\ \Omega$$

$$\text{Length} = \frac{R_{LINE}}{(\Omega/\text{mile}} = \frac{2200}{170} = 12.9\ \text{miles}$$

Larger diameter lines have less loop loss than smaller diameter lines in proportion to the resistance of their respective wire gauge. While these examples describe the effects of line resistance upon DC levels, the same resistive effects occur with the levels of AC signals that pass along these lines.

Inductance

If you look again at the parallel pair of wires that make up the simple transmission line, you should see that the conductors pass current which creates magnetic lines of force around them. Figure 5-2B shows the magnetic lines of force that result from current flowing through a 2-wire line. The electrical effect that corresponds to the creation of magnetic force from a changing flow of current is what we identify as inductance. Figure 5-2C shows the equivalent inductance of the wire-pair distributed along its length.

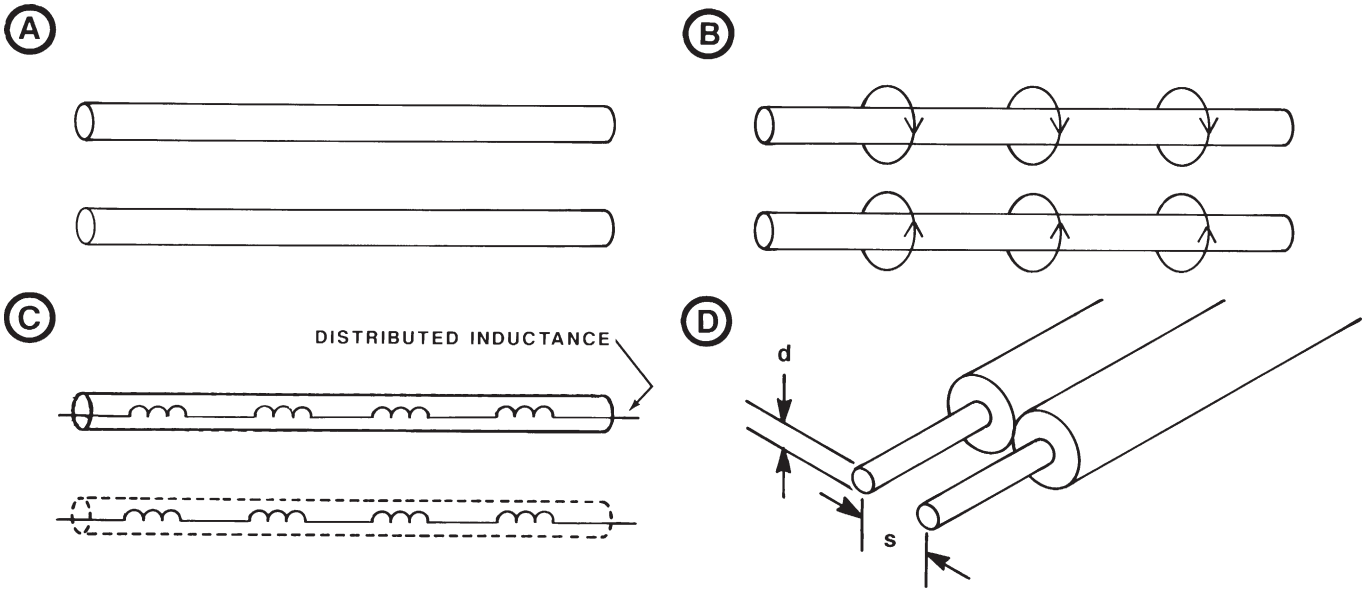


Figure 5-2
Distributed inductance.

The value of inductance (L), in henrys (H), of a reference length of a wire pair depends upon the diameter of its conductors, and the spacing of its conductors. The value of inductance is inversely proportional to the diameter of the wires, and directly proportional to the spacing of the wires. With the same diameters, the total inductance of a wire-pair is directly proportional to its length.

> The inductance of a transmission line is inversely proportional to the diameter of its wires, and directly proportional to the spacing of its wires.

With wire spacing as a variable, it is more convenient to calculate transmission line inductance than to list the values in a table. Transmission line inductance can be calculated with the following equation:

$$L = 280 \log\left(\frac{2s}{d}\right) \mu H/1000 \text{ ft.}$$

$$= 1.48 \log\left(\frac{2s}{d}\right) mH/mile$$

In the equation, "s" is the center-to-center spacing, in inches, of the two wires in the transmission line, and "d" is the diameter, in inches of one of the wires in the line. This is shown in Figure 5-2D.

The typical 22-gauge "twisted-pair" station wire used for a telephone cable drop has an on-center spacing of about 0.063 inches, while the diameter of the 22-gauge wire is about 0.025 inches. With this information, the inductance of the line, in units of miles, can be calculated as follows:

$$L = 1.48 \log\left(\frac{2s}{d}\right) \text{mH/mile} = 1.48 \log\left(\frac{(2 \times .063)}{.025}\right) = 1.04 \text{ mH/mile}$$

A 10-mile length of this transmission line will have a total inductance of 10.4 mH (10 × 1.04 mH/mile). Inductance has no effect upon the loop current from the talk battery of a telephone circuit. However, **inductance is one component of a transmission line's impedance**, which has significant effects upon information transfer, and audio-frequency signals, in telephone circuits. The effects of impedance will be described following a description of transmission line capacitance.

Capacitance

Figure 5-3 shows the effects of capacitance which result from an electrical charge applied to the two adjacent wires of a transmission line. The electrical charge is the difference in voltage across the line. It creates an electric field in the dielectric (insulating) space between the wires. The capacitance of the wire-pair is distributed along its length.

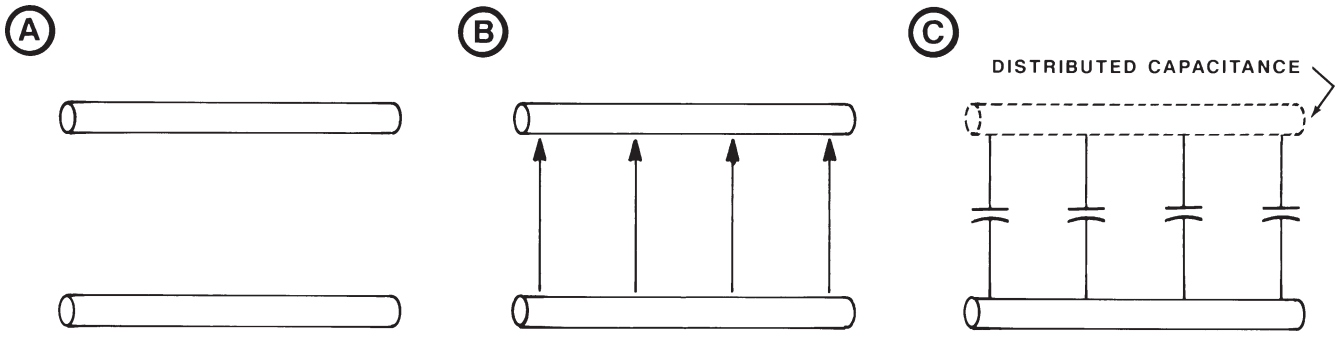


Figure 5-3
Distributed capacitance.

The value of capacitance (C), in Farads (F), of a reference length of a wire pair depends upon the diameter and the spacing of its conductors, just like line inductance. The value of capacitance is directly proportional to the diameter of the wires, and inversely proportional to the spacing of the wires. Note that this is opposite of the characteristics for inductance. With the same diameters, the total capacitance of a wire-pair is directly proportional to its length.

> The capacitance of a transmission line is directly proportional to the diameter of its wires, and inversely proportional to the spacing of its wires. These properties are opposite to that of inductance.

In addition to the diameter and spacing, the capacitance of a transmission line is affected by the properties of the dielectric material between the wires of the line. The voltage across the line creates an electric field in the dielectric space between the wires as shown in Figure 5-4. The property of the insulating material that affects a line's capacitance is called "dielectric constant." The value of the dielectric constant is identified by the Greek letter epsilon (ε).

> The capacitance of a transmission line is affected by the electrical property of its wire's insulating material. This property is called the insulator's "dielectric constant."

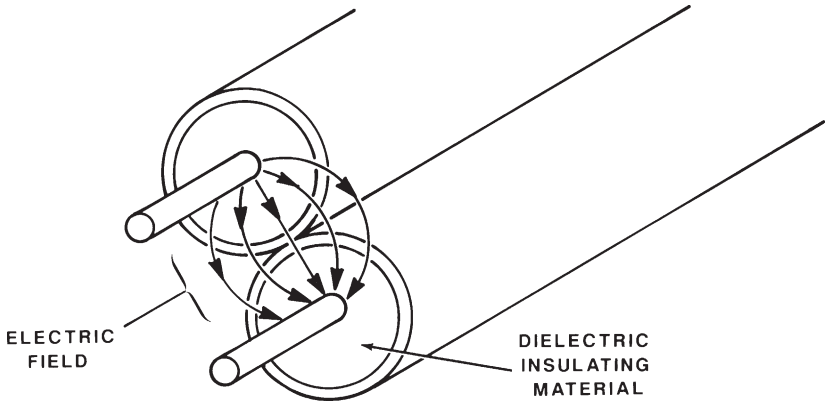


Figure 5-4

Effect of dielectric insulation.

The numerical value of the dielectric constant multiplies the capacitance between the conductors by its number. The dielectric constant of air is 1.0, which is the standard against which other dielectrics are specified. The dielectric constants of some popular insulating materials are listed in Table 5-2. If a transmission line with two bare, uninsulated wires has a capacitance of 10 pF/1000 feet, for example, an identical line with PVC insulation ($\varepsilon = 2.7$) will have a capacitance of 27 pF (2.7×10 pF).

Table 5-2

Dielectric constants of common materials.

DIELECTRIC CONSTANTS OF COMMON MATERIALS

Material	Dielectric Constant
Aluminum oxide	8.8
Titanium dioxide	100
Silicon dioxide (glass)	3.78
Epoxy resin	3.35
Polychlorotrifluorethylene	2.32
Polyethylene	2.25
Cellular polyethylene (polyfoam)	1.64
Polypropylene	2.25
Cellular polypropylene	1.56
Polystyrene	2.5
Polytetrafluorethylene (Teflon)	2.1
Polyvinylchloride (PVC)	2.7
Butyl rubber	2.35
Neoprene rubber	4.5
Balsawood	1.3
Douglas fir wood	1.9
Mica, glass, titanium dioxide	9.0
Soil, sandy, dry	2.5
Ice, pure	3.5
Water (distilled)	78

The capacitance of a transmission line can be conveniently calculated with an equation that accounts for wire diameter and spacing, and the dielectric constant of the insulating material, as:

$$C = 3.68\varepsilon \div \log\left(\frac{2s}{d}\right) \text{nF/1000 ft.}$$

$$C = 19.43\varepsilon \div \log\left(\frac{2s}{d}\right) \text{nF/mile}$$

As with the equation for calculating inductance, s is the center-to-center spacing of the two wires in the transmission line, and d is the diameter of one of the wires in the line, as shown in Figure 5-2D. The symbol ε is the dielectric constant of the insulating material shown in Table 5-2.

We can apply this equation to the same 22-gauge "twisted-pair" station line used in our previous examples. The line has an on-center spacing of about 0.063 inches, a wire diameter of about 0.025 inches, and a PVC dielectric (dielectric constant of 2.7). With this information, the capacitance of the line, in units of miles, can be calculated as follows:

$$C = 19.43\varepsilon \div \log\left(\frac{2s}{d}\right) \text{nF / mile}$$

$$C = 19.43 \times 2.7 \div \log\left(\frac{2 \times .063}{.025}\right) = 75 \text{ nF / mile}$$

The 10-mile length of this transmission line will have a total capacitance of 750 nF (10 × 75 nF/mile), or 0.75 μF. As with inductance, capacitance has no effect upon the loop current from the talk battery of a telephone circuit. However, capacitance is a critical component of a transmission line's impedance, which has significant effects upon information transfer and audio-frequency signals in telephone circuits.

IMPEDANCE AND PHASE

Recall that impedance is a prominent dimension of electrical components and circuits that pass and process signals. The text describes why transferring maximum signal power through a circuit requires that all circuit impedances are of the same value, matched. The text also describes how the electrical properties of a line are really a part of the load circuitry of a signal generator. Information about the impedance of a transmission line is, therefore, important in determining how efficiently signals pass along the line.

The impedances of transmission line networks affect their frequency response and bandpass characteristics. As signals pass from transmitter to receiver through such lines, they are likely to be degraded by the lines' electrical properties. If these electrical properties are known, however, corrections can be applied to reduce signal degradation. The corrections can be made with either electrical or electronic components.

Information about impedance is important in determining how efficiently signals pass along a transmission line, and in identifying corrections that reduce signal losses.

For signal paths typical of those found in local loop circuits, the transmission line functions as a simple RCL network. Using the R, L, and C values of our previous examples, we can evaluate the performance of a typical local loop circuit. The signals originate from a 600-ohm source (generator) at the CO, and connect to a 600-ohm telset through a 10-mile line between them. The connection is represented as a simplified circuit similar to that of Figure 5-5A. The series resistance is about 1700 ohms, the series inductance is about 10 millihenrys, and the parallel capacitance is about 0.75 microfarads.

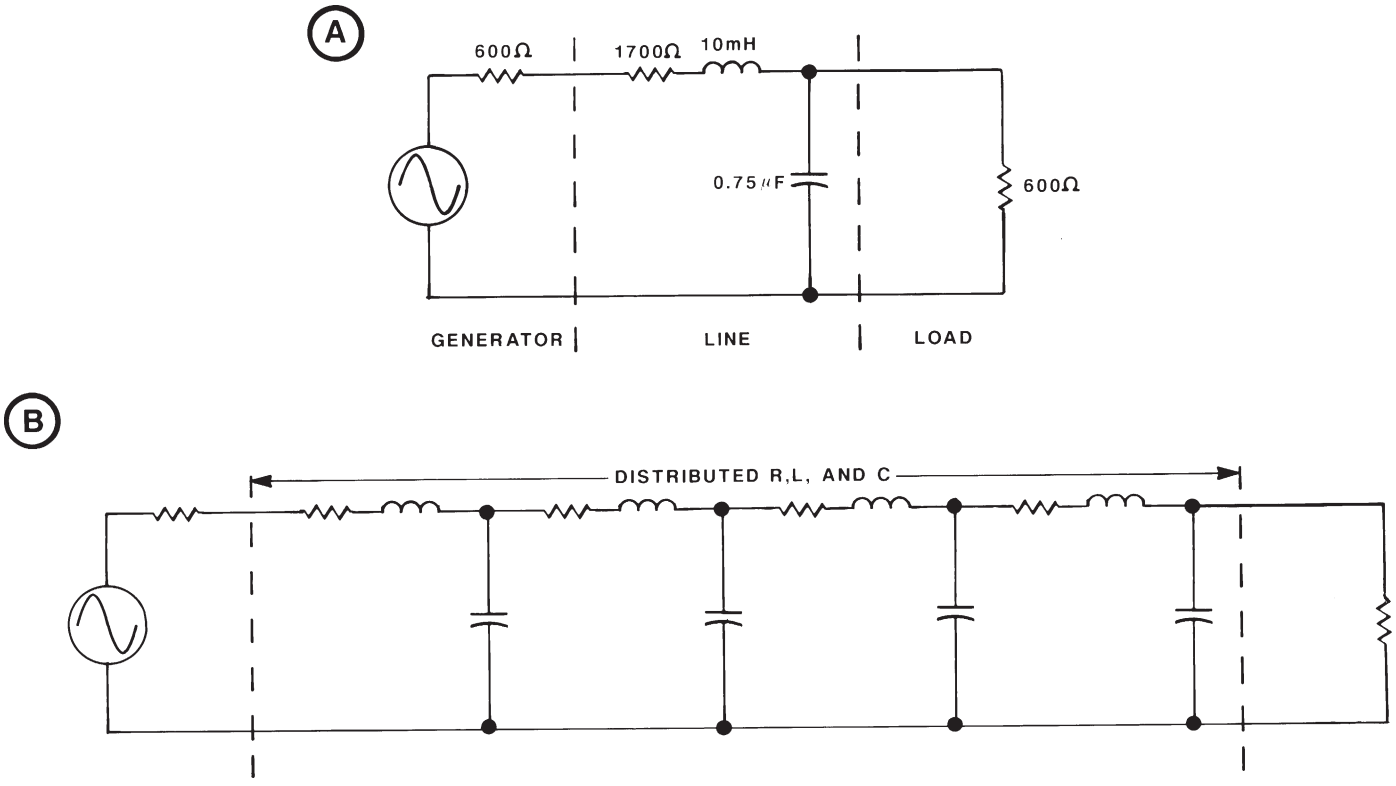


Figure 5-5
Distributed R, L, and C.

Figure 5-5A is not a truly accurate representation of a transmission line. The resistance, capacitance, and inductance are not lumped at specific locations on the line, as the diagram suggests. These properties are distributed along the entire length of the line. While it is not possible to precisely diagram distributed properties, the line can be more accurately represented in multiple sections, as shown in Figure 5-5B, with each RCL section accounting for only a small fraction of the total values of R, C, and L.

When a transmission line is used to carry signals for long distances, beyond the local loop, the line itself must have an impedance that allows signal generators to transfer power into it, and then to the load. In engineering jargon, "the generator sees the line, but can't see the load." The transmission line is said to "transfer the generator signal to the load."

Under these conditions, the impedance of the line is more critical, as it must match the impedance of the generator to accept maximum power from the generator. The line then carries the applied signal along its length to a load at some remote distance. The load impedance must also match the line impedance if maximum power is to transfer from the line to the load.

If impedances are not matched, losses will result. The loss due to mismatch is called "mismatch loss." The impedance of the transmission line used in this way is called "characteristic impedance" (Z_0). Almost all lines used for longer distance transmission are specified by their characteristic impedance value. The standard for two-wire transmission lines that carry audio and voice signals is 600 ohms.

> With long transmission lines, the generator applies power across the line's characteristic impedance. The line then transfers this signal to a distant load impedance.

A line's characteristic impedance is simply the ratio of voltage-to current of the signal on the line. That ratio remains the same for all points along the line, so long as the line is terminated with a load with an impedance identical to the line's characteristic impedance. The line's characteristic impedance is also equal to the square root of the ratio of the line's inductance-to-capacitance. The characteristic im-

pedance can also be calculated from the dimensions and dielectric constant of the two-wire line. Finally, values for L or C can be calculated if Z_0 and one of the other values are known. The equations used for these calculations are as follows:

$$\frac{V}{I} = \sqrt{\frac{L}{C}} = \frac{276}{\varepsilon} \log\left(\frac{25}{d}\right)$$

$$\frac{L}{C} = (Z_0)^2; \; L = (Z_0)^2 \, C; \; C = \frac{L}{(Z_0)^2}$$

For a 600-ohm line, terminated in a 600-ohm load impedance, the voltage-to-current ratio of the signal on the line is 600:1, and the inductance-to-capacitance ratio of the line's electrical properties is 360,000:1 or $(600:1)^2$.

The characteristic impedance can be calculated for the 22-gauge line used for local loop service from our earlier example. Recall that the inductance is 1 mH/mile, and the capacitance is 75 nF/mile. The characteristic impedance of this line can be calculated as:

$$Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{10^{-3}}{75 \times 10^{-9}}} \approx 115 \, \Omega$$

The impedance of this line is mismatched for a 600-ohm system, but because it is used in shorter-distance local loop services, it does not require that it be matched. The practice of purposely selecting lower impedance lines for local loop service is common, as a lower impedance line compensates for high-frequency losses, at the expense of overall mismatch losses. You will learn more about this later.

Phase Factors

Transmission lines are the electrical equivalent of inductive and capacitive elements that affect the phase shift of the signals which pass along them. The fundamentals of signal phase, phase shift, and wavelength are reviewed in the EB-551 Course. Recall that 2π radians phase shift is equivalent to one cycle (360°), and that the time period of one cycle is proportional to the square root of the product of L and C.

$$2\pi \text{ rads} = 360° = \sqrt{LC}$$

The velocity of a signal moving down a transmission line, therefore, depends upon the inductance and capacitance of the line. The highest velocity signals, such as radio waves, travel at virtually the speed of light. When signals pass through transmission lines, their velocity is reduced, due to the change in phase shift ("lag") imparted by the additional capacitance from the line's dielectric properties. The decimal value (or percentage) by which a signal's velocity is reduced, is called the transmission line's "velocity factor." The velocity factor is calculated as the inverse square root of the wire insulator's dielectric constant.

For the 22-gauge transmission line in our earlier example, its insulation was PVC, with a dielectric constant of 2.7. The velocity factor of this line is calculated as:

$$\text{V.F.} = \frac{1}{\sqrt{\varepsilon}} = \frac{1}{\sqrt{2.7}}$$

The velocity of a signal in this transmission line is only 61% of the same signal passing through air, or a line with air as an insulator and a dielectric constant of 1.0.

There is an additional complication about the phase and velocity of signals passing along transmission lines. With AC signals, the currents are confined to the outer surface or "skin" of the wires of a transmission line. As frequencies increase, this depth of current flow gets thinner. The resistance of the wires is higher because there is less conductive area on the wire's surface than is available through its entire cross section. Also, the inductance of the wires is less at higher frequencies because all of the current is confined to the wire's outer surface. Larger diameter wires have less inductance. This phenomena is called the "skin effect."

With less inductance, the velocity factor becomes greater, because higher frequencies travel faster than lower frequencies. When this effect is significant, it is called "phase distortion." Phase distortion is undesirable in communication systems, so corrective measures are also applied to compensate for this effect in transmission lines and circuits.

COAXIAL CABLES

In addition to two-wire transmission lines, coaxial cables (coax) are used extensively in communication circuits and systems. While it is not used for direct voice communication, coax is used in higher-frequency circuits that process voice signals. Coax is truly a two-conductor line, but one of its conductors is concentric to the other. Figure 5-6 shows the general structure of a coax cable. Its outer conductor can be fabricated of braided fine wires for flexibility, or of solid semi-rigid tubing.

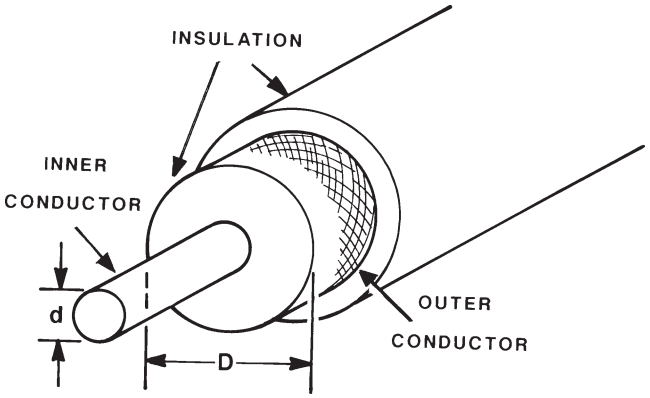


Figure 5-6
Coaxial cable.

The major advantage of coaxial cables is their shielding properties. Their grounded outer conductors prevent the signals within the cables from radiating beyond their inside surface; and they prevent other signals from outside their structure from penetrating their surface. Coaxial transmission lines can be packed side-by-side without one interfering with the other, a feature that is impossible to achieve with unshielded wire-pair lines.

Coaxial cables prevent interference from their placement adjacent to other cables or wires.

The electrical properties of coaxial cables depend upon their physical dimensions, and insulating materials, just like the wire-pair lines. The equations for these properties are as follows:

$$L = 140 \log\left(\frac{D}{d}\right) \mu H/1000ft = 740 \log\left(\frac{D}{d}\right) \mu H/mile$$

$$C = 7.35\varepsilon \div \left[\log\left(\frac{D}{d}\right)\right] nF/1000\ ft. = 38.8\varepsilon \div \left[\log\left(\frac{D}{d}\right)\right] nF/mile$$

$$Z_0 = \left(\frac{138}{\sqrt{\varepsilon}}\right) \log\left(\frac{D}{d}\right)$$

Consider a coaxial cable with a center conductor of 22-gauge wire (0.025 inch diameter) and an outer conductor inner-surface diameter of 0.15-inch. The dielectric constant of its polyethylene insulating material is 2.25. Its electrical properties are calculated as follows:

$$L = 140 \log\left(\frac{D}{d}\right) = 140 \log\left(\frac{0.15}{0.025}\right) = 109\ \mu H/1000\ ft.$$

$$C = 7.35\varepsilon \div \left[\log\left(\frac{D}{d}\right)\right] = 7.35 \times 2.25 \div \left[\log\left(\frac{0.15}{0.025}\right)\right] = 21\ nF/1000\ ft.$$

$$Z_0 = \left(\frac{138}{\sqrt{\varepsilon}}\right) \log\left(\frac{D}{d}\right) = \left(\frac{138}{\sqrt{2.25}}\right) \log\left(\frac{0.15}{0.025}\right) = 72\ \Omega$$

This concludes your study of the electrical properties of wires and cables that are critical to their use as transmission lines. These properties are applied to these lines when they are used to transmit signals in the next chapter.

SUMMARY

Communication signals and messages require transmission media to transfer information from one location to another. The fundamental media used for transmission are wires and cables. These transmission lines are essentially electrical networks of resistance, inductance, and capacitance, that are distributed along the length of the lines. The values of these R, L, and C elements depend upon the geometry and characteristics of the wires in the lines, their diameter and spacing. The line's capacitance also depends upon the properties of the material used to insulate the wires. These values can be easily calculated if the physical properties of the line are known.

The impedance of transmission lines depends upon their electrical properties, primarily inductance and capacitance. The impedance, in turn, affects the line's frequency response, and signal power transfer through them. The shunt capacitance of transmission line impedances significantly reduces the level of higher frequency signals on the lines, and any non-linearities in the electrical properties of the line affect the velocity and phase shift of signals which pass through the lines.

The two popular transmission lines used for telecommunication service are two-conductor "twisted-pair" and coaxial cables. The two-wire lines are inexpensive, but radiate and receive induced signals. Coaxial cables have the advantage of shielding, and are immune to radiating and receiving induced signals. Coax is a superior transmission line, but its capacitance is greater, and it is more lossy than two-wire line. Both types of line serve the specific needs of communications systems.

SELF-TEST REVIEW

1. List six of the transmission media used for communication signals. _____
   _____

2. Which wire has the highest resistance?

   A. 1000 ft of 26-gauge.
   B. 0.5 mile of 22-gauge.
   C. 1 mile of 19-gauge.
   D. 2 miles of 16-gauge.

3. Calculate the loop resistance of a 22-gauge 2-wire line that is 5 miles long. _____

4. Calculate the loop current through a 10-mile 24-gauge wire-pair, when the telset is off hook. The telset has 200 ohms DC resistance, and 48VDC is provided by the CO current source. _____

5. What is the smallest wire diameter (gauge) that can be used for a 20-mile loop to provide at least 20 mA DC from a 48-volt current source, if the DC telset resistance is 200 ohms? _____ gauge

6. Which transmission line have the greatest inductance?

   A. 26-gauge spaced at 0.080 inches on-center.
   B. 22-gauge spaced at 0.120 inches on-center.
   C. 19-gauge spaced at 0.160 inches on-center.
   D. 16-gauge spaced at 0.220 inches on-center.

7. Calculate the distributed inductance of a 22-gauge 2-wire line that is 5 miles long. The line's conductor spacing is 0.2 inches. _____

8. Which transmission line has the greatest capacitance (assume the same dielectric for each)?

   A. 26-gauge spaced at 0.080 inches on-center.
   B. 22-gauge spaced at 0.120 inches on-center.
   C. 19-gauge spaced at 0.160 inches on-center.
   D. 16-gauge spaced at 0.220 inches on-center.

9. Calculate the distributed capacitance of a 22-gauge 2-wire line that is 5 miles long. The line's conductor spacing is 0.2 inches, and its dielectric insulator is PVC. _____

10. A signal generator has a source impedance of 600 ohms. Which load impedance will provide for the highest power transfer from source to load?

    A. 100 ohms.
    B. 150 ohms.
    C. 200 ohms.
    D. 900 ohms.

11. Which transmission line will have the greatest attenuation of higher-frequency signals (assume the same dielectric for each)?

    A. 26-gauge spaced at .080 inches on-center.
    B. 22-gauge spaced at 0.120 inches on-center.
    C. 19-gauge spaced at 0.160 inches on-center.
    D. 16-gauge spaced at 0.220 inches on-center.

12. Which transmission line has the greatest characteristic impedance (assume the same dielectric for each)?

    A. 26-gauge spaced at 0.080 inches on-center.
    B. 22-gauge spaced at 0.120 inches on-center.
    C. 19-gauge spaced at 0.160 inches on-center.
    D. 16-gauge spaced at 0.220 inches on-center.

13. A 75-ohm coaxial cable has a specified distributed capacitance value of 20 pF/ft. Calculate its distributed inductance. _____ nH/ft.

14. Calculate the velocity factor of a transmission line with dielectric insulation of Teflon®. _____

15. Which transmission line has the greatest phase distortion of higher frequency signals?

    A. 26-gauge spaced at 0.080 inches on-center.
    B. 22-gauge spaced at 0.120 inches on-center.
    C. 19-gauge spaced at 0.160 inches on-center.
    D. 16-gauge spaced at 0.220 inches on-center.

16. Calculate the distributed inductance, capacitance, and characteristic impedance of a coaxial cable with the following properties: 26-gauge center-conductor, 0.080 inches inner diameter, outer conductor, Teflon dielectric insulator, and 1000 feet long.

    Inductance _____
    Capacitance _____
    Impedance _____

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CHAPTER 6 — Conditioning of Lines and Circuits

INTRODUCTION

Transmission lines are lossy; they will always have less power at their outputs than is applied to their inputs. The input-to-output power ratios of signals along a transmission line are specified in units of dB. Just the relatively short length of a typical 1200-ohm local loop will, for example, reduce a signal from the telco's CO by more than 6 dB. Wire and cable losses for longer-length circuit paths are significantly greater.

The losses to higher-frequency signals are greater as they pass through transmission lines (wires and cables). With two parallel wires, the capacitance of the lines becomes significant if the length of the lines is great. The result is that higher-frequency signals are both phase shifted and bypassed to ground. The resulting frequency response of the cable indicates a slope of increased signal loss.

Complete transmission circuits include amplifiers to compensate for cable losses, and other electrical elements to cancel the capacitive effects of cable loss. The transmission circuits also include attenuators to reduce the levels of signals when necessary for specific requirements. In all, the effects of transmission lines and circuits upon signals are compensated within the transmission systems of the communications network. The techniques of signal conditioning (changing signal level and/or frequency response) introduced in Chapter 5 of this text, are applied extensively to transmission systems in compensating for cable and circuit effects.

The techniques of signal conditioning include changing the levels of signals and the frequency response of circuits. Signal conditioning is applied extensively to transmission systems in compensating for cable and circuit effects.

Specifications and Measurements

The reliability and quality of communication systems are critical factors. Business and industry depend upon the availability of telephone services for their operations. To function effectively, governments depend upon reliable telephone services. Using the telephone is the first act taken in almost every emergency. Aside from social communication, the availability of telephone services to almost everyone in our world has become a necessity for the activities of everyday life.

To assure reliability and quality, communication systems must be correctly installed, and performance tested and maintained on a continuing basis. Some of the testing processes are so often performed, that special computers are used to continually check the circuits of the PTN. While modern electronic equipment and techniques are used for testing, the installation and maintenance of the vast telephone system also requires substantial work be done by the hands of skilled, knowledgeable people. The last part of this chapter describes the standards required for correct installation and operation of the telephone system.

The most fundamental of system testing is related to signal transmission. Test signals are applied to one end of transmission lines and circuits, and their power and frequency characteristics are measured at the other end of their transmission paths. The extent to which the signals are degraded in passing through the circuits provides a measure of the circuits' performance.

For telephone voice communication circuits, test transmission measurements are made in reference to standards for power level, frequency response, circuit bandpass, line loss, noise, and distortion, among others. Similar measurements are made for communication circuits designed for data and video signals. The emphasis of this text is on fundamentals and voice telephony, so we will review only those techniques appropriate for measurement of analog audio signals that are applied to voice-grade transmission circuits.

Most transmission measurements are performed manually with a single specialized instrument that was designed specifically for transmission circuit and signal testing. The instrument is called a "transmission impairment test set" ("TIMS-set"), or just a "transmission test set." This instrument includes sections for generating, detecting, and measuring audio-frequency signals, and it includes reference standards for measuring the performance of transmission circuits.

To assure reliable operation of transmission circuits, measurements are routinely made with automatic computerized testing equipment. As with the TIMS-set, these computerized instruments are specialized to perform specific tasks, and to display data about the operation of communication services. The complications of such automatic test equipment clouds the concepts required to understand the purposes of measurement techniques, and your ability to interpret the results of measured data obtained from this equipment. For this reason the last part of this chapter describes how to use measurements in simplified form, with the goal of understanding concepts over procedures.

OBJECTIVES

When you complete this chapter, you will be able to:

- Define the techniques used to condition transmission lines to pass signals with uniform frequency response and minimum loss.
- Describe and calculate the effects of shunt capacitance upon the frequency response and signal losses within transmission lines.
- Describe how loading coils are used and the effects of placing them along transmission lines to cancel the effects of capacitance upon a line's frequency response.
- Describe how amplifiers are used and the effects of placing them within transmission circuits to compensate for a line's frequency response and attenuation characteristics.
- Identify the major operating standards for transmission lines and circuits used in voice-channel telecommunication practice.
- Identify the specifications of C-type and D-type line conditioning, and the operating standards they define.
- Define the units of measurement used by telco in defining critical power levels of signals and noise within transmission lines and circuits.
- Identify and describe the fundamental measurements and setups used to evaluate the performance of transmission lines and circuits.

SIGNAL LOSSES AND CONDITIONING

The signal losses in a transmission line can be determined from the electrical properties of that line. In Figure 6-1, we have calculated some equivalent network values which are typical of a transmission line circuit. To better understand these electrical properties, without forcing you through the tedium of extensive calculations, we have made some circuit translations for this figure.

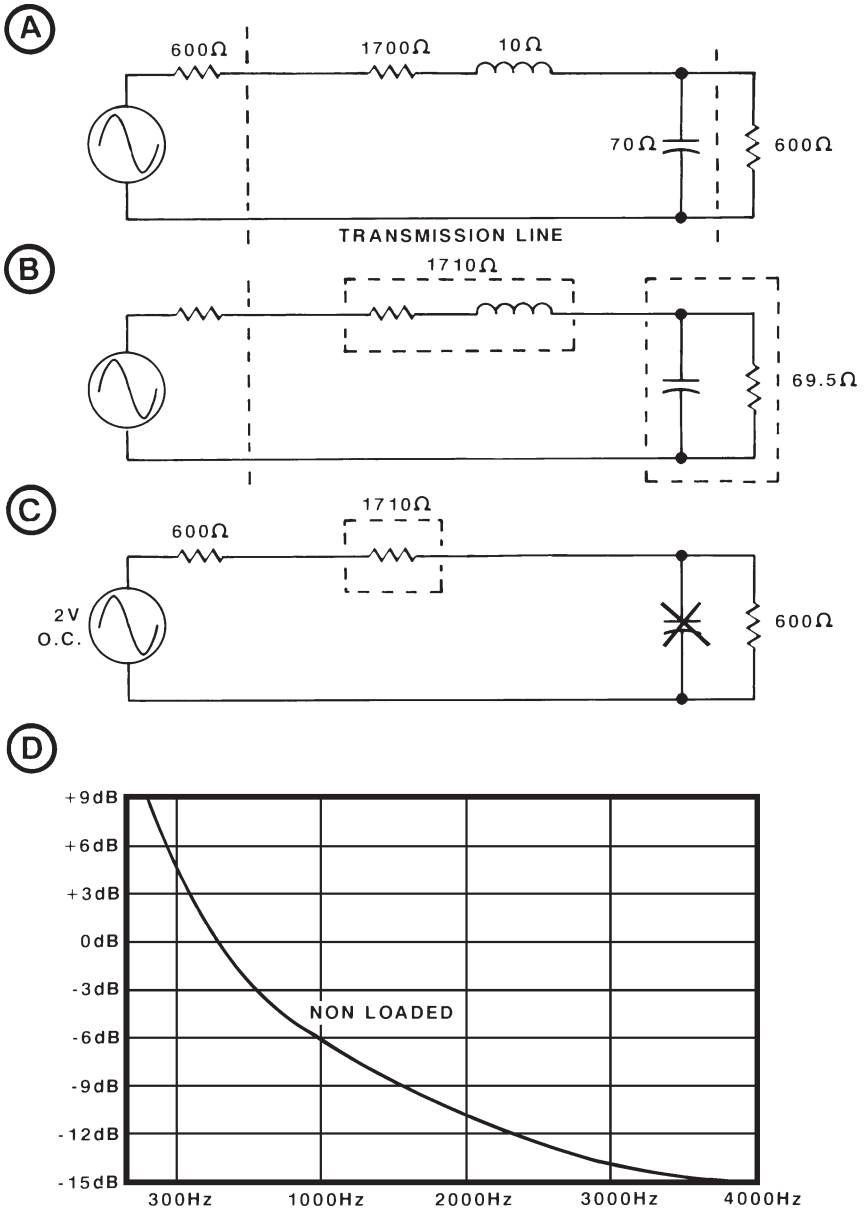

Figure 6-1

Shunting effect of parallel line capacitance.

The circuit is first drawn as a lumped RLC network equivalent to the transmission line circuit, as shown in Figure 6-1A. A 600-ohm generator impedance, representing the CO, is shown at the left driving the line, and a 600-ohm load impedance, representing the telset, is shown at the far right terminating the line. At a frequency of 3 kHz, the reactances of the line's inductance and capacitance are 188 and 70 ohms respectively.

Figure 6-1B shows how we can separate the series and parallel (shunt) portions of the circuit to analyze its operation. Without resorting to the complications of phase angles or complex impedances, we can generalize some impedance values for the series portion of the circuit, and for the parallel portion of the circuit.

First, adding 188 ohms of series inductive reactance to the 1700 ohms series line resistance only slightly increases the series portion of the impedance to about 1710 ohms, an insignificant change. Next, placing the 70 ohms of capacitive reactance in parallel with the 600-ohm load resistance of the telset shunts the load impedance. This results in a significantly lower equivalent impedance for the parallel network. The 70 ohms of capacitive reactance, in parallel with 600-ohms load resistance, yields an impedance of 69.5 ohms, a value much lower than the desired 600 ohms. The capacitance, therefore, presents a substantial load across the 600-ohm telset.

When a signal is applied to this circuit from the generator, the voltage remaining across the 69.5 ohms of parallel impedance is low. If the parallel impedance is 600 ohms, the load voltage is at its highest level available to the telset. The shunting effect of the capacitive reactance, therefore, drops the signal voltage available to the load impedance.

> A transmission line's series inductance has little effect upon signal levels. The line's shunt capacitance, however, has a substantial effect upon the level of the signals transferred through the line.

We can calculate the shunting effect of the capacitance for a 3 kHz signal by applying two simplified voltage-divider equations to the circuits in Figure 6-1. We'll assume that the generator's open-circuit voltage is 2 VAC. First, we can assume an ideal circuit with no

capacitance. Under ideal conditions, the voltage across the 600Ω load, using the circuit in Figure 6-1C, is calculated as:

$$V_{LOAD} = V_{OC}\left(\frac{R_{LOAD}}{R_{GEN} + Z_{SER} + R_{LOAD}}\right)$$

$$= 2\left(\frac{600}{600 + 1710 + 600}\right) = 0.412 \text{ Volts}$$

$$Loss_{dB} = 20 \log\left(\frac{V_{LOAD}}{V_{OC}}\right) = 20 \log\left(\frac{0.412 \text{ V}}{2 \text{ V}}\right) = -13.7 \text{ dB}$$

Now, repeat the calculation with the actual shunting effects of the capacitance in the circuit, using the circuit in Figure 6-1B (neglect phase):

$$V_{LOAD} = V_{OC}\left(\frac{Z_{LOAD}}{R_{GEN} + Z_{SER} + Z_{LOAD}}\right)$$

$$= 2\left(\frac{69.5}{600 + 1710 + 69.5}\right) = 0.058 \text{ V}$$

The effect of the capacitance in this example has reduced the level of the 3 kHz signal from an ideal of 412 millivolts down to 58 millivolts. The equivalent loss that results from this shunt effect can be calculated in dB as:

$$Loss_{dB} = 20 \log\left(\frac{V_{LOAD}}{V_{OC}}\right) = 20 \log\left(\frac{0.058}{2}\right) = -30.7 \text{ dB}$$

Similar calculations can be made on equivalent circuits for lower frequencies of operation, where the capacitive reactance values are higher, and the shunting effects are less pronounced. The results of these calculations, and the measured results of actual circuit performance, will yield a general frequency response graph. The graph will appear similar to that of Figure 6-1D, for a "non-loaded" line. At lower frequencies, the parallel load impedance is near 600 ohms, so the load voltage is high. As frequency increases, the shunting effect of the capacitance reduces the load impedance. The load voltage is likewise reduced in proportion to that impedance.

Line Loading

To improve the frequency response of transmission lines and circuits, it is necessary to cancel or compensate for the shunt effects of capacitance. One practical technique uses additional inductors in series with the wires of transmission lines. This technique is used extensively in telephone practice, and it is called "line loading." The inductors used for line loading are appropriately called "loading coils."

> The techniques of line loading with loading coils are used to cancel the effects of a line's shunt capacitance, and improve its frequency response.

You can best understand the function of loading coils by reviewing the transmission line as an RLC network, using Figure 6-1 as a reference. Every series network can be converted to an equivalent parallel network, and vice versa. If we convert the series inductance of Figure 6-1A to its parallel equivalent, we can redraw the LC components of the transmission line as represented in Figure 6-2A. The equivalent value of inductive reactance, in shunt at 3 kHz, is 190 ohms, much higher than the 70 ohms of shunt capacitive reactance.

The loading effect of the capacitive reactance can be canceled by making the equivalent shunt inductive reactance also approximately 70 ohms. Increasing the series inductance results in a lower equivalent shunt reactance, ideally canceling the effects of the line's capacitance, as shown in Figure 6-2B. Figure 6-2C shows the graphed results of the loaded line, compared to the non-loaded line.

Line loading with actual inductors of large-diameter wire does not suffer the problems associated with distributed wire inductance, such as skin effect. Loading thus tends to reduce phase distortion, as well as improve frequency response in transmission lines. The benefits of inductive line loading were learned early in telephone service, and extensive calculations and experiments were performed by Bell Labs to establish standards for loading practices. The results of this work include standards used by telcos to specify the inductance value and placement of loading coils for almost all of the transmission lines used in telephone service.

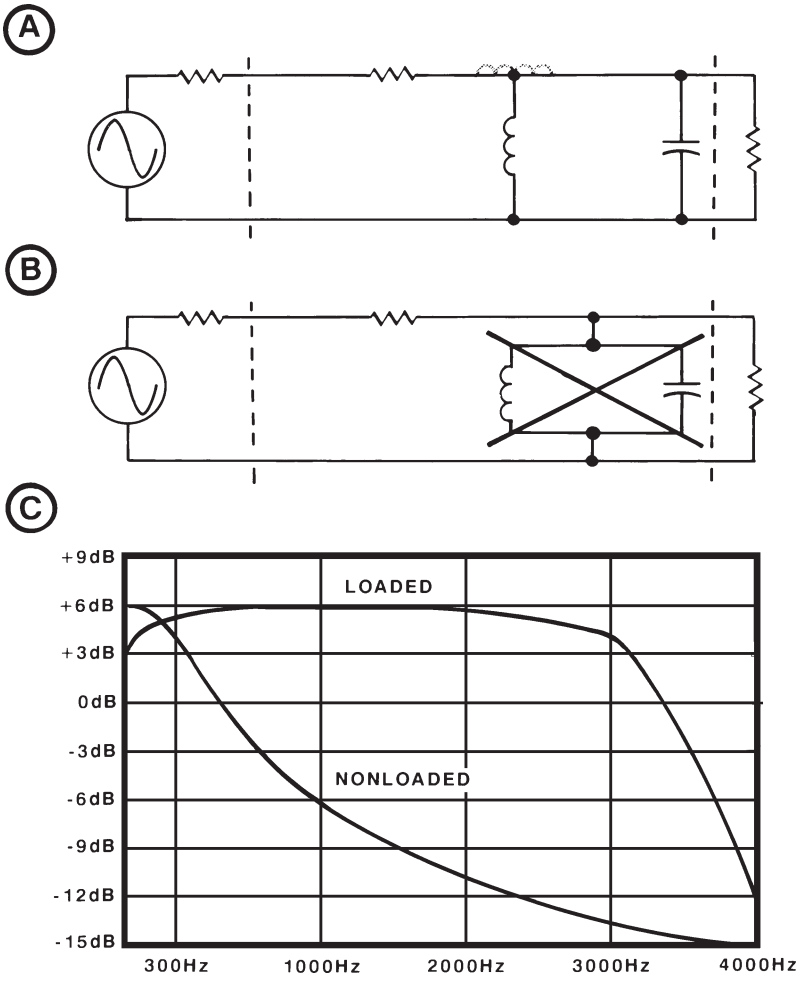

Figure 6-2

Loading coil cancel capacitive shunting.

Line Compensation

The loading of transmission lines somewhat compensates for their unequal frequency response, but loading does not compensate for the signal power losses encountered by a signal passing along a line. In fact, loading improves frequency response at the *expense* of power efficiency. We can't expect miracles, or something for nothing, however, as all measures taken to improve electrical performance are made at some cost. The advantage of loading is that the coils do not require a source of DC power for operation, but they do take power from the signals they pass.

With modern technology, the most practical way to fully compensate for the limitations of transmission lines is with electronic amplifiers. The cost of amplification is DC power, the most abundant form of power available in telecommunication systems. The amplifiers convert DC power into signal power to raise the level of the signals applied to their inputs. Both the frequency limitations and efficiency of transmission lines can be practically compensated with the use of electronic amplifiers.

> Electronic amplifiers compensate for the frequency response and power losses of transmission lines; they do so by using DC power for operation.

The basic function of an amplifier is to increase the power level of the signal applied to its input, and to do so without distorting the waveform of that signal. In application, the dB values of power losses, from one point on a cable to another, are compensated by equivalent dB values of gain from an amplifier placed within the transmission path of a signal. In addition to compensating for signal power losses, an amplifier's frequency response is easily adjusted to obtain uniform power levels over a much wider range of frequencies than can be obtained from loading coils.

In practice, the electrical performance of the line, and its losses, are first evaluated without amplification. Amplifiers are then applied to correct (compensate) for line losses and frequency response. Figure 6-3A shows a typical frequency response graph of an unloaded cable. Figure 6-3B shows the response of a compensating amplifier over the same range of frequencies. Figure 6-3C shows the results of combining these circuits. The frequency response plot on the graph of the transmission line is said to "slope" (downward) as frequency increases; while the plot of the amplifier is said to "tilt" (upward) as frequency increases.

The placement of compensating amplifiers must be at moderate distances, where the signals on the transmission line are still significantly higher than any noise and interference on the line. If the amplifier spacing is too great, the line signal is reduced to a level near that of electrical noise and weak interference signals. An amplifier, placed in such a location, amplifies the noise in the same proportion as the signal, which creates a degraded signal even though its level is high. The objective is to keep the noise low in proportion to the signal, a high signal-to-noise ratio.

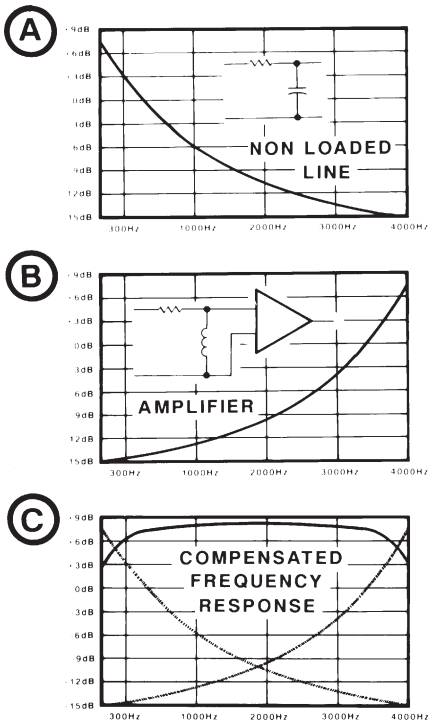

Figure 6-3

Amplifier compensation of transmission line.

CONDITIONING STANDARDS

Standards have long been established for voice and data communication through transmission lines and circuits. These standards include specifications for power, frequency, phase, and signal-to-noise response of transmission lines and the signals they pass. In telephone practice, line conditioning is specified as C-type and D-type.

C-type conditioning indicates recommended specifications for frequency and phase (phase distortion) response, called "attenuation distortion" and "phase delay," in telco jargon. D-type conditioning indicates recommended specifications for signal-to-noise (S/N), and harmonic and intermod distortion. In communication practice, C-type conditioning is applied to all transmission circuits, while D-type conditioning is critical for data transmission circuits.

> C-type conditioning specifies attenuation distortion and phase delay, while D-type conditioning specifies signal-to noise, and harmonic and intermod distortion.

C-Type Conditioning

Figure 6-4 shows the standard C-message weighting curve. This frequency response is standard for almost all telephone voice transmission circuits. The curve evolved from the response of the human ear. You may recall that the reference frequency for sensitivity of the ear is at about 1000 Hz. This is also the reference peak response (telco actually specifies 1004 Hz) of the C message weighting curve.

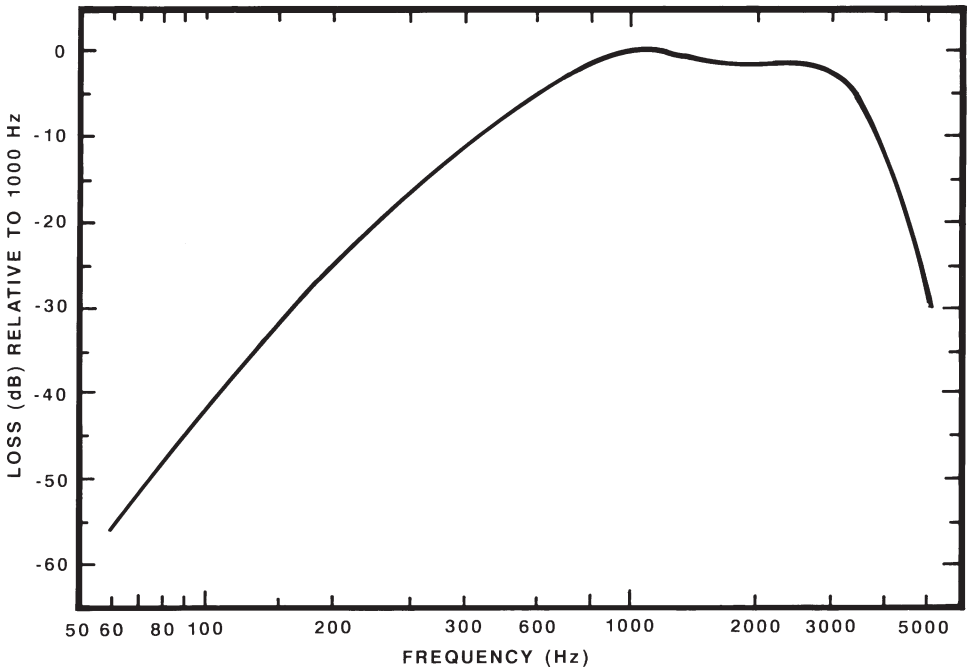

Figure 6-4

C-message weighting curve.

C-type conditioning specifies the standard values referenced for the frequency response curve of Figure 6-4. The frequency range from 500 to 2500 Hz allows a variation of +2 to –8 dB in reference to the 1004 Hz reference level; the range from 300 to 3000 Hz allows a variation of +3 to –12 dB above and below the reference level. There are some minor variations in these values for specific transmission services.

The phase delay (also called "envelope delay") distortion specifications for C-type conditioning, recommends a maximum variation in time between frequency limits. Recall that the velocity factor in lines and cables varies with frequency due to wire skin effect. Higher frequency signals have a greater velocity than lower frequency signals. Therefore, the lower frequencies are delayed in passing through a length of line. The standard delay specifications for C-type conditioning is 1.75 milliseconds for frequencies from 800 to 2600 Hz.

D-Type Condition

With frequency limits from 300 to 3000 Hz, and C-message weighting, voice information is clearly communicated with signal-to-noise ratios as low as 20 dB (10:1 voltage ratios, and 100:1 power ratios), although 24 dB S/N is recommended. For data transmission, however, noise levels must be lower, with corresponding higher S/N ratios. D-type conditioning specifies a minimum of 28 dB S/N for transmission circuits conditioned for data and higher-quality voice signals.

The actual specification of noise and S/N ratios depends upon the measurement technique used to evaluate noise power and circuit performance. Some of these measurement techniques are described later.

D-type conditioning also specifies transmission circuit linearity by indicating the maximum harmonic and intermod distortion imposed upon signals passing through the circuits. Because transmission lines are RLC circuits, they are linear, and do not distort waveforms. When amplifiers, or other electronic elements, are connected within transmission circuit paths, however, some amount of non-linearity is inevitable. The specification for D-conditioned circuits is that the levels of the harmonic intermod products are at least 35 to 40 dB below the level of a reference 1004 Hz signal.

Specifications

Table 6-1 details the major Bell System specifications for signal transmission within a C-message weighted voice channel. The following text describes how these specifications are applied to transmission facilities.

Table 6-3

Facility Parameters.

SUMMARY OF FACILITY PARAMETER LIMITS

Parameter	Limit
1004-Hz loss variation	Not more than ±4 dB long-term
C-message noise	Maximum rms noise at modem receiver (nominal −16 dBm point)
Facility miles	*dBm*
0-50	−61
51-100	−59
101-400	−58
401-1000	−55
1001-1500	−54
1501-2500	−52
2501-4000	−50
4001-8000	−47
8001-16000	−44
C-notched noise	(minimum values)
(a) Standard voice band channel	24-dB signal-to-C-notched noise
(b) High-performance line	28-dB signal-to-C-notched noise
Single-frequency interference	At least 3 dB below C-message noise limits
Nonlinear distortion	At least 35 dB
(D-conditioned circuits only)	At least 40 dB
Signal-to-second order	Reading of 50 minimum end to end with standard P/AR meter
Signal-to-third order	
Peak-average ratio	

The terminal equipment designed to interface with transmission circuits is specified at 600 ohms, with this impedance value measured at 1004 Hz and 0 dBm.

In telco jargon, the reference TLP (transmission level point) identifies a required or specified power level. TLP is specified in units of dBm, except for 0 dBm. Thus, 0 TLP is a required power level of 0 dBm, while a level of –10 dBm TLP is a required power level of –10 dBm. If the

specified alignment level of a signal into an amplifier is –12 dBm, for example, the specification is indicated as "–12 dBm TLP." Signal levels vary, however, depending upon the range of circuits through which they pass, so the actual signal level at the amplifier's input may *not* be –12 dBm, even though –12 dBm is its optimum alignment level. (For data transmission, the alignment level is often specified as DLP for data level point.)

In contrast to TLP levels, telco uses another power reference, dBmO. dBmO is the actual signal level referenced to it's TLP level. With an alignment level at the input of an amplifier specified at –12 dBm TLP, but an actual input signal level of –9 dBm, the level is indicated as "+3 dBmO." The level of –9 dBm is 3 dB above what it should be at –12 dBm TLP.

$$\text{Signal}_{\text{dBm}} = (\text{dBm TLP}) + \text{dBmO} = (-12) + (+3) = -9 \text{ dBm}$$

There are similar power references for noise. Telco identifies a reference for noise power with the letters "rn" for reference noise. rn is always referenced at a level of –90 dBm (1 pW). The actual value of noise power, in a transmission circuit with C-message weighting, is identified as "dBrnC." A noise level of +20 dBrnC is at –70 dBm; 20 dB above –90 dBm, and 20 dB above rn.

$$\text{Noise}_{\text{dBm}} = \text{rn} + \text{dBrnC} = (-90) + (20) = -70 \text{ dBm}$$

Signal-to-noise (S/N) ratios are best calculated based upon actual levels in dBm. A signal level of +2 dBmO, at a point specified as –7 dBm TLP, is at a true power level of –5 dBm. The noise level in that signal is +57 dBrnC, which is at a true power level of –33 dBm (57 dB above –90 dBm). The S/N is calculated as:

$$\text{S/N}_{\text{dB}} = [(\text{dBm TLP}) + \text{dBmO}] - (\text{rn} + \text{dBrnC})$$

$$\text{S/N}_{\text{dB}} = (-7+2) - (-90+57) = (-5) - (-33) = 28 \text{ dB}$$

MEASUREMENTS

Regular maintenance of transmission lines, circuits, and facilities requires accurate measurement of their performance. The measurement techniques and procedures are standardized, and there is a variety of specialized test equipment to perform them. With the increased of computer management of facilities, most routine measurements are now automated. As with all automated test systems, however, it is important to understand the concepts for each of the measurements performed, otherwise the data obtained from the tests are meaningless.

> Although most transmission measurements are routinely performed using automated or semi-automated test equipment, it is important to understand the concepts of each measurement procedure, otherwise the measured data from testing is meaningless.

The evaluation of frequency characteristics, compliance with C-message weighting, signal power levels, and circuit gain or loss is accomplished with a single frequency response measurement procedure. Figure 6-5 shows the generalized test set-up for this procedure. A signal of known level, usually 0 dBm (0 TLP), is applied through a 600-ohm source impedance to the transmission facility under test. The signal generator steps through the range of frequencies within the voice channel, and a power sensor (meter) at the other end of the transmission facility indicates the power level at each of the frequencies generated. The output may be either in tabular or graphical form, and evaluated in reference to the C-message weighting curve of Figure 6-4. The power level in reference to 0 TLP at 1004 Hz (or 1.0 kHz) indicates the circuit loss (or gain).

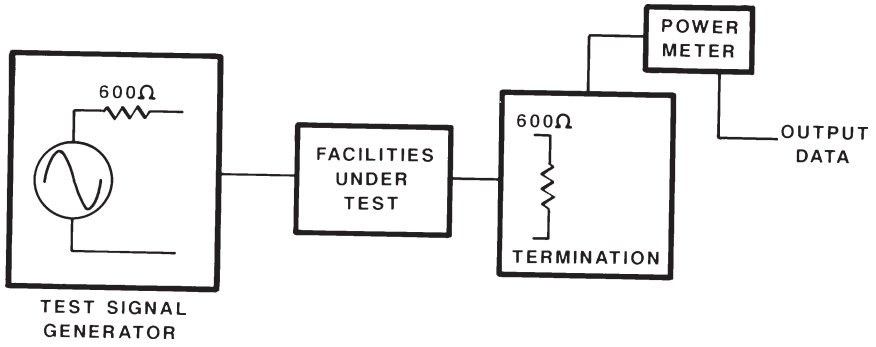

Figure 6-5

Measuring power and frequency response.

C-message noise measurement is used to evaluate the noise power within a transmission circuit when there is no signal in the circuit. The measurement set-up, as shown in Figure 6-6A, uses a power meter only to measure the noise power. Very often, however, the level of circuit noise with no signal present, is not the same as the circuit noise when there is a signal in the circuit. Measurement of noise while a signal is present is called "C-notched noise." Figure 6-6B shows this test set-up, with the addition of a 1 kHz signal generator and 1 kHz notch filter to the set up of Figure 6-6A. The filter removes the signal just ahead of the noise-measuring power meter.

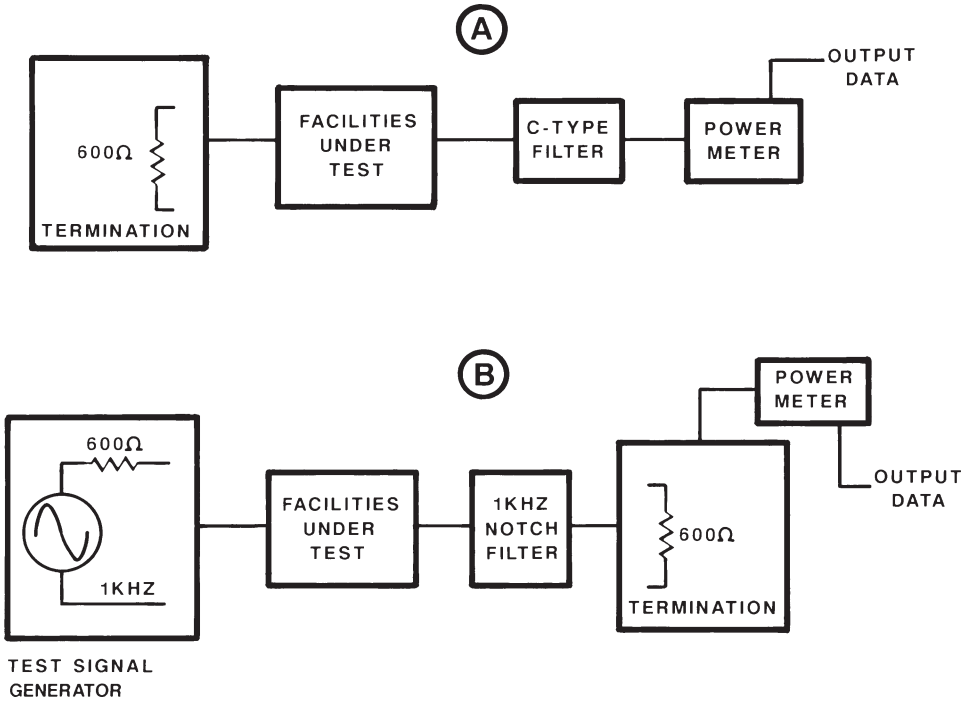

Figure 6-6

Measuring noise.

Evaluation of transmission circuit linearity for harmonic distortion is accomplished with a signal generator, filters, and power meter. Figure 6-7A shows this set-up. A signal of 704 Hz (an industry standard) is first applied to the power meter through the transmission facilities, then through a C-message filter, to establish a power reference level. A 704 Hz notch filter, or an 800 Hz high-pass filter, is then placed within the signal path to remove the 704 Hz fundamental frequency; leaving only the power of the harmonics to pass to the power meter.

The difference between the harmonic signal levels and total power is measured in dB at the power meter. Calculations are required to adjust the data to the D-type conditioning specifications.

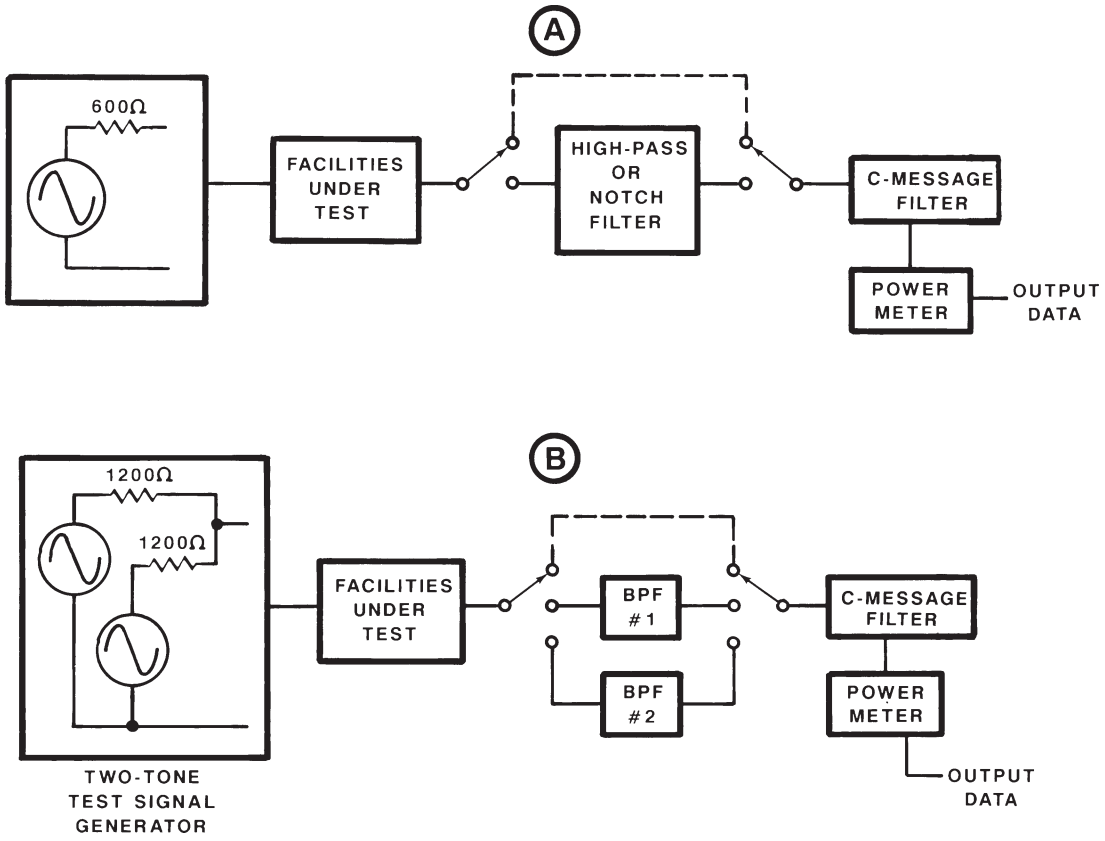

Figure 6-7

Measuring distortion.

Evaluation of a transmission circuit's linearity for intermod distortion is similar to that for harmonic distortion. However, this procedure requires two signal generators. Figure 6-7B shows this set-up. Signal frequencies of 856 and 1374 Hz are first applied to the power meter to establish a reference level. A bandpass filter at the sum frequency of 2330 Hz is then placed within the signal path to pass only the intermod signal to the power meter. The difference between the intermod signal level, and the level of the total power, is measured in dB at the power meter. Calculations are required to adjust the data to the D-type conditioning specifications.

The standard procedures for measuring phase (envelope delay) distortion rely upon the integration of pulse waveforms that result from non-linear inductance or capacitance in transmission circuits. A short duty-cycle pulse signal is first applied to the transmission circuit. If the circuit has non-linear phase properties, the pulses will spread, which extends their duty cycle. Figure 6-8A shows the results of phase distortion on a pulse waveform.

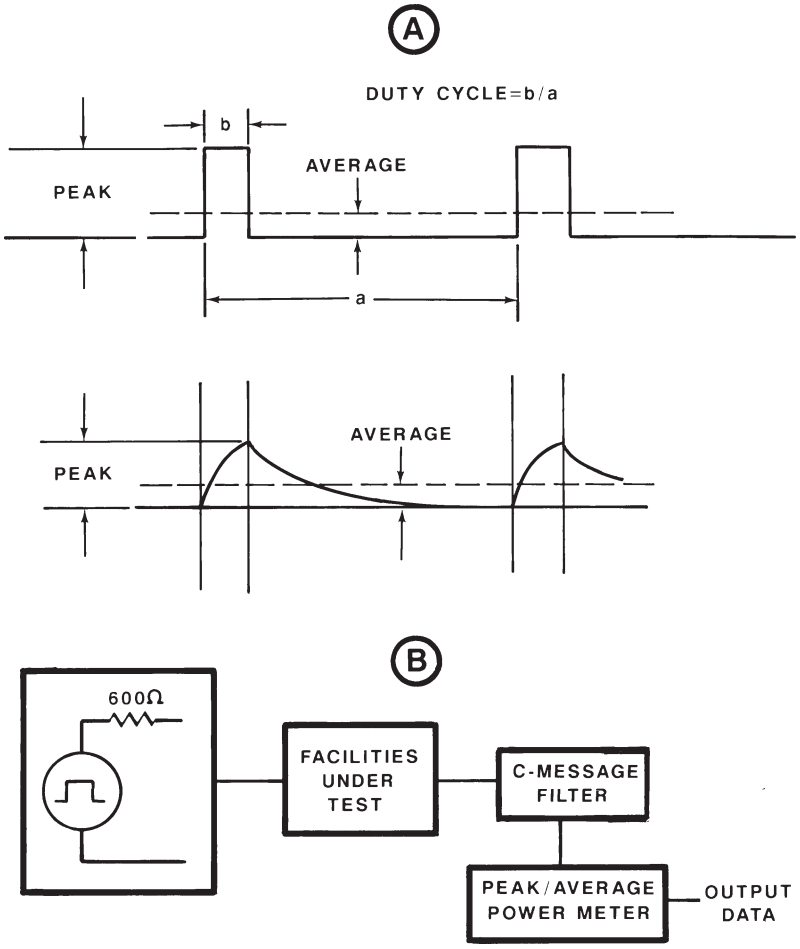

Figure 6-8

Measuring peak/average ratio.

The effects of phase distortion are evaluated by the extent to which the duty cycle is distorted. The duty cycle is first referenced for a ratio of peak-to-average power (P/AR), the peak power of the pulse, compared to the average power over one cycle of its operation. A special power meter is used for this measurement and set-up as shown in Figure 6-8B. The meter can read both instantaneous peak power (of the pulse) and the average power of the pulse signal.

The ratio between the two power levels is established as 100 (100%) for the signal directly out of the pulse generator. After passing through the transmission facilities under test, the P/AR will be degraded by the phase distortion in those circuits. The standards in absolute numbers, between 0 and 100, have no units of measurement, and are only reference numbers for comparison. The minimum acceptable P/AR is 50 (50%).

There are many other performance standards and measurements for the transmission of high-speed data, video, and digital communication signals through specialized facilities and circuits. The concepts presented here are primarily applied to voice circuits and lower-speed data circuits. They serve as an introduction to the specialized measurements that are regularly used to maintain the quality of communication services.

SUMMARY

The effects of shunt capacitance are significant in affecting losses to the higher-frequency signals that travel through transmission circuits. Techniques called "line conditioning" are applied to correct this problem. The basic technique is to apply inductance along the line with loading coils. The loading coils essentially cancel the effects of capacitance to improve the high-frequency response of transmission lines. This process trades off overall line loss for uniform frequency response.

Electronic amplifiers are used, rather than loading coils, or in conjunction with loading coils, to increase the level of signal power lost through transmission. Electronic amplifiers have the advantage of compensating for both the power losses and frequency response characteristics of transmission circuits. The disadvantages of the amplifiers include their cost and their possibility of adding distortion and noise to the signals which pass through them.

To insure the proper transmission of signals, telcos have established technical standards for signal power levels, equipment impedance levels, and transmission circuit frequency response, distortion, and noise limits. These standards are specified as C-type and D-type line conditioning in voice channel telephone systems. Communication services are designed to meet or exceed these conditioning standards, and to share the same units of measurement in quantifying these standards.

To insure that the standards are met, there are extensive test and measurement procedures applied within communication services. The measurements for transmission lines and circuits include signal power levels, equipment impedance levels, and transmission circuit frequency response, distortion, and noise limits; the same properties that are specified for the line-conditioning standards. While most of these measurements are made routinely by automated test equipment, the concepts of the measurements are basic, and they must be fully understood to interpret the data obtained from the automatic measurements.

SELF-TEST REVIEW

1. The transmission line has electrical properties equivalent to a network of:

   A. series R, shunt L, and shunt C.
   B. series R, series L, and shunt C.
   C. series R, shunt L, and series C.
   D. shunt R, series L, and shunt C.

2. Calculate the voltage across the 600-ohm load, first without the capacitor, as in the circuit in Figure 6-1C, and then with the capacitor, as in the circuit in Figure 6-1B. Complete your calculations for 2 kHz, where X_L is 126 ohms, and X_C is 104 ohms. V_{OC} is 2 volts. Finally, calculate the loss in dB at 2 kHz for the equivalent network of the transmission line.

   V_{LOAD}(w/o cap) _____ $Loss_{dB}$ _____

   V_{LOAD} (w/cap) _____ $Loss_{dB}$ _____

3. A loading coil is placed in a transmission line with electrical properties at 2 kHz equal to those you calculated in Question 2. Its effect is to reduce the line's capacitance by a factor of 10, which raises its reactance from 104 to 1040 ohms. Repeat your calculations for Question 2, to determine the reduced loss at 2 kHz, as affected by the loading coil.

   V_{LOAD} (w/coil) _____ $Loss_{dB}$ _____

4. A transmission line has a 12 dB signal loss at 1 kHz, and a 20 dB loss at 3 kHz. Specify the operating characteristics of an amplifier that can be used to compensate for the line losses. _____

   _____

5. Identify which type of conditioning, C or D, applies to the following specifications:

   _____ A. Signal-to-noise.
   _____ B. Signal power.
   _____ C. Frequency response.
   _____ D. Harmonic distortion.
   _____ E. Attenuation distortion.
   _____ F. Envelope delay distortion.
   _____ G. Intermodulation distortion.
   _____ H. Phase delay.
   _____ I. Circuit linearity.

6. Which two of the electrical properties (RLC) of a transmission line change in proportion to frequency, due to skin effect? Why?

   _____

7. What are telco's standard frequency, power, and impedance reference levels? _____

8. What are the maximum allowable levels (in dBm) of C-message noise in transmission circuits of 70 and 500 miles in length?

   _____

9. What is the specified S/N of C-notched noise (in dB) for a standard voice channel transmission line? _____

10. The input to an amplifier in a transmission circuit is specified for a signal level of –16 dBm TPL. The signal at that point is measured at a level of –4 dBmO. What is the power level of the signal? _____ dBm

11. A noise power level is specified at +53 dBrnC. What is the power level of the noise? _____ dBm

12. What is the S/N for the operating values calculated in Questions 45 and 46? _____ dB

13. Draw a block diagram of the set-up required to measure the frequency response and attenuation distortion (power loss) of a transmission circuit. (Attempt to draw this from memory.)

14. Draw a block diagram of the set-ups required to measure the C message and C-notched noise of a transmission circuit. (Attempt to draw this from memory.)

15. Draw a block diagram of the set-ups required to measure the harmonic and intermod distortion of a transmission circuit. (Attempt to draw this from memory.)

51. Describe how and why the P/AR of a transmission circuit becomes lower as the length of the circuit increases. _____

_____

_____

52. Describe how P/AR can be used as an indirect means of determining the envelope delay (phase distortion) of a transmission circuit. _____

_____

_____

Section 3

Advanced Telephone Systems

CHAPTER 7 — Business Telephone Systems

INTRODUCTION

Earlier chapters of this course described the process of getting a telephone call from one telset to another. You learned about the various signals that are used in the basic telephone service and the telephone equipment itself. You also learned how signals are generated and detected, and how these signals are processed to make up for losses and noise. But these chapters only dealt with a typical telephone call from an ordinary phone like you would find in a residence to a phone in another residence.

Depending upon the size of a particular business, a separate residence-type telephone line to each telset in the business could be very cost-prohibitive. This is especially true when only a few of these lines are used at any given time to place or receive outside calls. This is where the idea of a business phone system comes into play.

Some of the advantages of a business telephone system are listed below:

- The ability to make telephone calls within the business without tying up outside lines. With ordinary residence-type telephone connections, a conversation between two employees would tie up two telephone lines; one from the each phone to the central office. With a business telephone system, calls within the business could be handled internally.

- The ability to reduce the number of telephone lines required between the business and the central office. Because only a few outside lines are needed at any given time, a reduced number of outside lines could be shared among all of the telephones within the business.

- Ease of transferring a call from one phone to another.

- Capability to have music-on-hold or pre-recorded information about the company while a caller is waiting to speak to someone.

Business telephone systems can be either analog or digital. Analog systems reproduce voice, computer data, and video signals directly, while digital is more reliable and can operate at much higher speeds. The majority of today's business telephone systems are analog, but as new systems are installed or older systems are upgraded, digital is becoming more popular. Unfortunately, analog and digital telephones are typically not compatible with both types of systems without the proper interfaces. In addition, some digital telephone systems use proprietary interfaces which are not compatible with other brands of KSUs (key service units).

There are three major types of business telephone systems. These are the Key Telephone System, Private Branch Exchange (PBX), and Central Exchange (Centrex). Although over the years its become harder to identify one system from the other, especially when a particular company may utilize a combination of these systems, this chapter will describe each of them separately.

OBJECTIVES

When you complete this chapter, you will be able to:

- Describe the differences between key, PBX, and Centrex telephone systems.
- List the steps required to make an outside call with both key and PBX systems.
- Describe the main blocks that make up a key service unit.
- Describe the main blocks that make up a PBX system.
- Explain the purpose of a CODEC.
- Explain how a wireless PBX system works.

KEY TELEPHONE SYSTEM

Key telephone systems are generally used by smaller companies which require less than 100 telephones. You can usually identify this system by the multiple phone line buttons on its telsets as shown in Figure 7-1. These telsets are commonly referred to as 1A2 telephone sets, KTUs (key telephone units), or key sets.

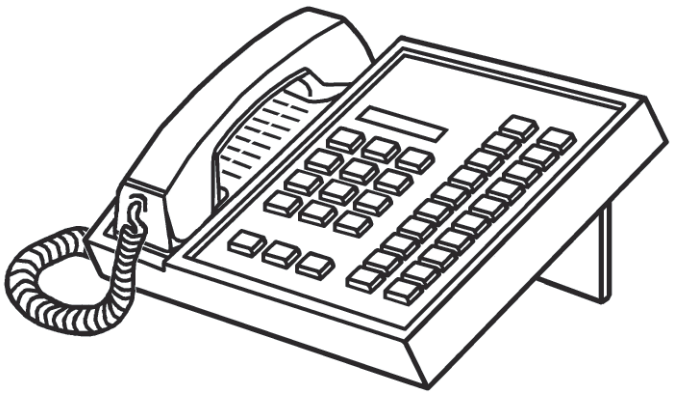

Figure 7-1

Typical 20-line key system telset.

Older key systems used large cables with bulky connectors to connect the telsets to junction boxes. All of the available phone lines were actually connected to each telephone, and the switching took place right inside the telset.

Newer, digital systems use a much smaller cable which contain only a few wires. Typically one pair of wires carry the talk and listen audio, while another pair of wires provide switching signals. There may be additional wires for special features. The actual switching is done at another location inside the business.

To place a call, users first push a button to select an unused outside line, and then enter the telephone number they wish to call. Indicator lights show which lines are busy. Because the user has to select an outside line, key telephone systems are not generally considered to be switches.

Because not all phones are not being used at the same time, the good rule of thumb is to have one outside line for each four telsets in the system.

A block diagram of a typical system is shown in Figure 7-2.

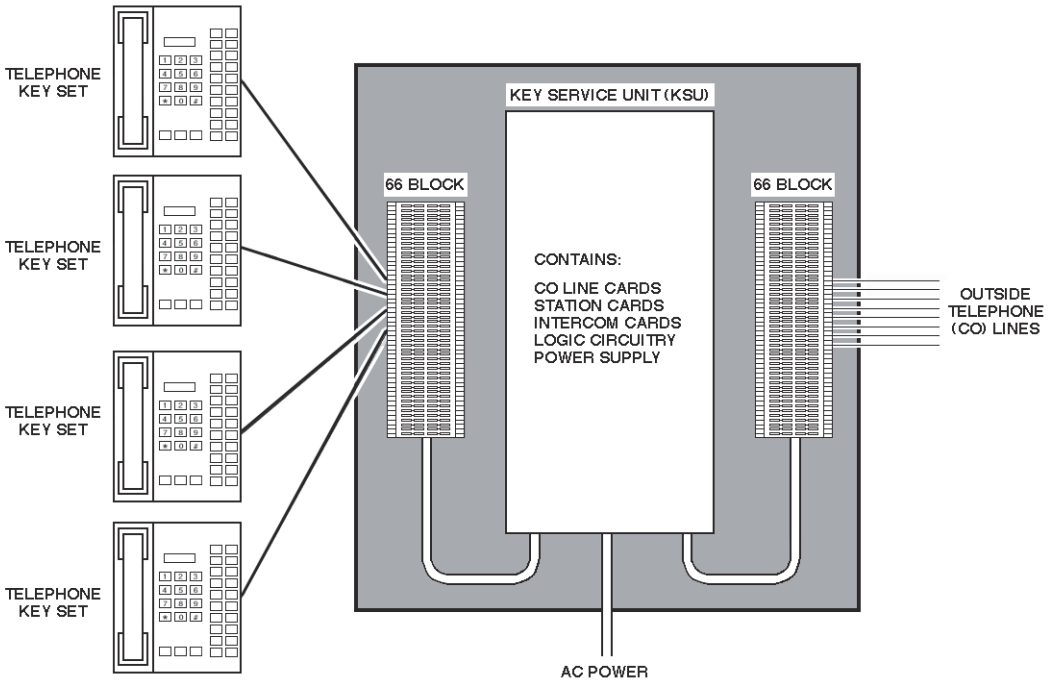

Figure 7-2

Block diagram of a typical key system.

The Key Service Unit (KSU) is the heart of the key telephone system. Each of its major sections are described below.

The CO line cards are the interface between the other parts of the KSU and the outside telephone lines. These cards, instead of the individual telephones, advise the central office when a telephone requests an outside line.

The station cards are the interface between the CO line cards and key sets which are connected to the local system. They process the control signals between each key set and the central processor unit (CPU).

The intercom cards may or may not be used. When they are present, they allow communication between key sets in the system without going through the outside lines and the CO.

The logic circuitry controls the operation of the entire system.

The power supply converts the AC power to the voltages required by the various KSU circuits.

Some of the features now available with key telephone systems are music-on-hold, paging, caller ID, voice mail, 3-way or conference calling, speed dial, and speakerphones. These features generally require an external computer to incorporate them.

PRIVATE BRANCH EXCHANGE (PBX)

Another type of system you will find in a medium- or large-sized business environment is the private branch exchange (PBX) or private automatic branch exchange (PABX). The first PBX systems required a live operator. As telephone system technology grew, they became automatic and a live operator was no longer required. Therefore, these systems became known as PABXs. Today, all of these systems are automatic, so they again became known simply as PBXs. Many of today's PBXs are controlled by internal computers. Modern PBXs are expandable to handle several thousand telephones.

Although earlier PBX systems used analog technology, newer PBXs use digital technology. A PBX's digital signals can be converted to analog when it is connected to a local loop which is still analog. Analog systems are sometimes called POTS, which is an acronym for plain old telephone service.

PBXs connect a telset within a business to an outside telephone line. They are considered to be private systems because they are owned and operated by the particular business and are located inside their building. They are also branch exchanges because they allow employees to make telephone calls within the business just like an outside telephone exchange allows subscribers to make calls to other subscribers. To allow calls within the business, PBXs generate their own dial tone instead of obtaining it from the local CO. Have you ever noticed that when you picked up a business phone the dial tone seemed to sound a little different after you dialed the "9" to obtain an outside line? That's because the first dial tone you heard was generated by the PBX, and the second dial tone was generated by the CO.

PBXs are often referred to as switches, and the groups of outside telephone lines are referred to as trunks (high-capacity connections) which are leased from the local CO. Trunks may be set up to allow only incoming calls, only outgoing calls, or a combination of the two.

PBX systems also feature direct inward dialing (DID), which allows an outside caller to use a dedicated telephone number to directly call a specific employee. At first, this concept may be a little hard to grasp,

because there may be many more telephone numbers assigned to the business than there are actual outside lines. What happens is the CO switches a DID call to one of the business's trunk lines, and then the PBX switches the call to the correct employee.

One way you can tell the difference between a key telephone system and a PBX system is how you go about making an outside call. As you recall, to make an outside call with the key system, you first select an unused outside line, and then dial the number you want. With a PBX system, however, you just dial a "9" to automatically select an outside line, and then dial the number. You generally don't know, or even care, which line you are using. If you call someone with caller ID, their unit may indicate an unfamiliar telephone number. Telephone numbers assigned to businesses generally fall into sequential groups, but if other lines are added later, they could be anything within the particular exchange.

A block diagram of a typical PBX system is shown in Figure 7-3.

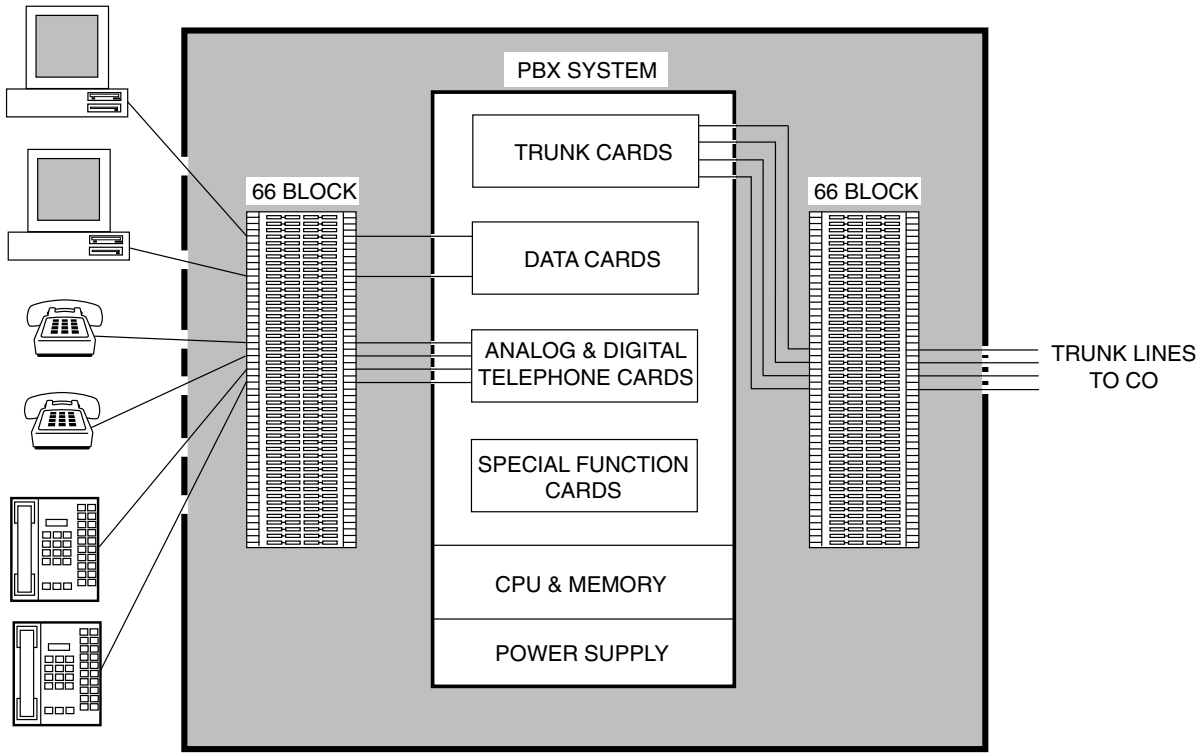

Figure 7-3

Block diagram of a typical PBX system.

The trunk cards form an interface between the other parts of the PBX and the CO's trunk lines.

The data cards form an interface between computers and the PBX.

The analog and digital telephone cards allow you to connect both analog and digital telsets to the PBX. As the name implies, analog phones connect to the analog cards and digital phones connect to the digital cards.

The special function cards allow you to customize the system, and incorporate new features at a later time.

The CPU and memory controls the operation of the entire system.

The power supply converts the AC power to the voltages required by the various circuits. Many systems now use battery-backup to keep the system running during a power failure.

Some of the features supported by PBX systems include voice mail, call forwarding, conference calling, call holding, call waiting, call restriction, and multiple phone lines.

DIGITAL PBXs

All PBXs made today are digital. A CODEC (coder-decoder) in the telset converts your voice (analog) into a digital signal before it passes through the cable to the PBX. If the PBX is connected to a CO which still uses analog technology, the PBX must convert the digital signal to an analog signal. In some cases, the PBX may need to do a digital-to-digital conversion to change the digital signal into the proper format for the CO. This is necessary because the digital signal from the telset to the PBX is a unipolar signal (never goes below zero) whereas the signal between the PBX and the CO is a bipolar signal (goes above and below zero).

WIRELESS PBX

No discussion of PBX would be complete without describing one of its more modern features. Wireless PBX is an add-on to a conventional wired PBX which allows you to answer phone calls arriving at your desk even when you are away from it. A wireless PBX extension works similar to a home cordless phone, except that it works at a much higher frequency. In many cases it may remind you of a cellular phone, except

that it has a much more limited range. Some wireless PBX portable phones can even automatically switch to a regular cellular system when they detect that they are out of range of the PBX base station(s).

A typical wireless PBX system would use one or more base stations situated on the business premises to provide the best possible coverage. Figure 7-4 shows a typical wireless PBX system which uses two base stations.

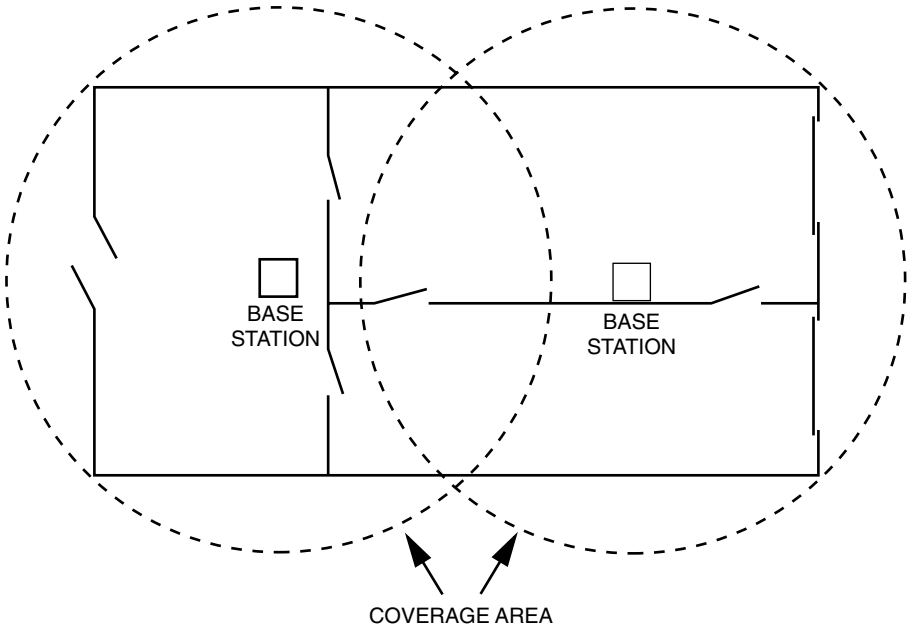

Figure 7-4

Typical wireless PBX system.

Note how the coverage areas of the base stations overlap to include all areas of the business. You will learn more about this concept of "cells" when you learn about cellular telephone systems in the next chapter.

CENTRAL OFFICE EXCHANGE (CENTREX)

Central office exchange (Centrex) is similar to PBX, except the switching equipment is located at the local CO instead of at the business. Each telephone line is connected directly to the local CO, where they form a Centrex group which has a standard set of 7-digit phone numbers. Centrex actually uses a partition of the CO's equipment to provide private telephone service to businesses.

Figure 7-5 shows that the various lines at the business are multiplexed into a data stream and then sent to the central office.

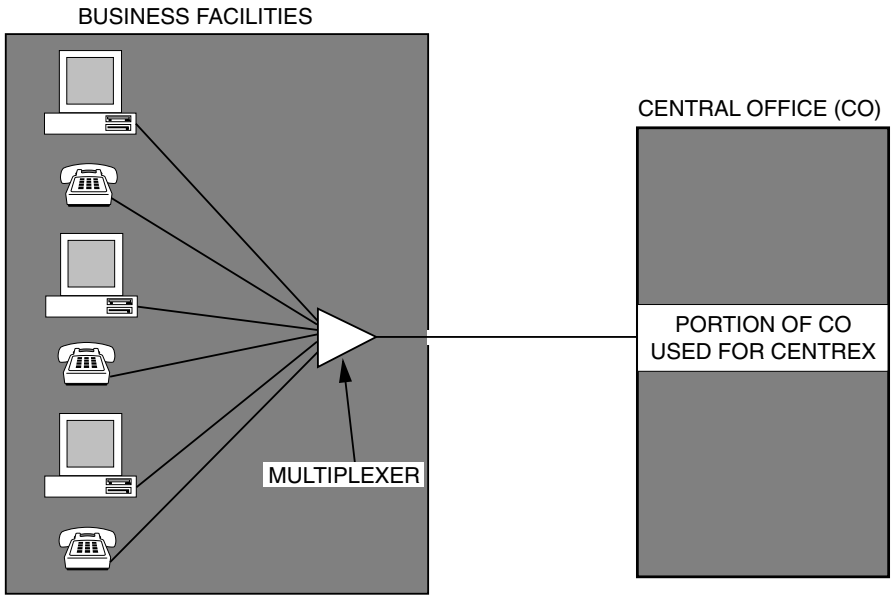

Figure 7-5

Typical Centrex system.

One benefit of the Centrex system is that the telephone company owns the equipment, so the business can avoid a large initial capital outlay, except for the telsets themselves. The telephone company can also regularly maintain and update the equipment, without requiring the business to buy new equipment.

Some of the features available with Centrex systems are call forwarding, call pickup, call transfer, automatic callback, call waiting, conference calling, priority ringing, speed dialing, voice mail, and electronic mail (email).

SUMMARY

In this chapter, you learned about the differences between key, PBX, and Centrex telephone systems. In recent years, those differences have become blurry.

With key systems, the user has to push a button to select a specific outside line. With PBX systems, simply presses the "9" key and the PBX automatically selects an outside line. A telephone in the Centrex system mimics an ordinary home-type phone.

Key and PBX systems are usually installed on the business premises, while Centrex systems are located on the local telephone company's premises.

Some installations may be made up of a combination of key and PBX systems. These are called hybrid systems and can accommodate both key and PBX telsets.

Although at one time both analog and digital were used, all PBXs made today are digital. A CODEC in a PBX telset converts your voice into a digital signal before it is sent to the main PBX unit. Depending upon the type of equipment installed at the local CO, the digital signal may need to be converted back to analog, or be changed into a different type of digital signal.

Wireless PBX systems allow you to carry a portable PBX-type phone with you as you move about in a building.

Centrex systems are owned, maintained, and operated by the telephone company, while most key and PBX systems are owned by the particular business, and are installed on their premises.

SELF-TEST REVIEW

1. How do you access an outside line with a key telephone system?

   A. Dial a "9".
   B. Press a button to manually select a particular line.
   C. Just remove the handset from its cradle.
   D. Remove the handset from its cradle and tell the operator you want to make an outside call.

2. Key telephone systems are not generally classified as switches.

   A. True.
   B. False.

3. If you have twelve telsets in a typical key telephone system, how many outside lines should you normally have?

   A. 24
   B. 12
   C. 6
   D. 3

4. Which of the following systems uses a KSU?

   A. Key system.
   B. PBX system.
   C. Centrex system.
   D. All of the above.

5. Which of the following process the control signals between a telset and the CPU?

   A. Line cards.
   B. Station cards.
   C. Intercom cards.
   D. Trunk cards.

6. How do you access an outside line with a PBX system?

   A. Dial "O".
   B. Dial "9".
   C. Push a button to select an unused line.
   D. Just remove the handset from its cradle.

7. In a PBX system, which of the following statements is true.

   A. Trunks can be set up to allow only incoming calls.
   B. Trunks can be set up to allow only outgoing calls.
   C. Trunks can be set up to allow a combination of incoming and outgoing calls.
   D. All of the above.

8. In the telephone industry, what is POTS?

   A. Plain old telephone system.
   B. PBX-only telephone system.
   C. Private-onsite telephone system.
   D. Personal online technical survey.

9. In a PBX system, the PBX gets its own dial tone from the CO.

   A. True
   B. False.

10. Which of the following is not present in a PBX system?

    A. Trunk cards.
    B. Analog and digital cards.
    C. KSU.
    D. Data cards.

11. What is the main purpose of a CODEC?

    A. To convert analog to digital.
    B. To convert digital to analog.
    C. To convert one type of digital signal to another type of digital signal.
    D. To provide security to a telephone conversation.

12. Which of the following statements is true?

    A. Wireless PBXs allow you to carry your PBX-type phone with you.
    B. Base stations are used to improve the coverage of a wireless PBX phone within a business.
    C. Some wireless PBX portable phones can automatically switch to a cellular system when they are out of range of a PBX base station.
    D. All of the above.

13. Centrex switching equipment is usually located at the CO.

    A. True
    B. False

14. Who owns the switching equipment in a Centrex system?

    A. The business.
    B. The telephone company.
    C. The manufacturer.
    D. There is no equipment to own.

CHAPTER 8 — Cellular Telephone

INTRODUCTION

With increasing numbers of people spending more and more time in their vehicles, the need to communicate while on the move also increased. There needed to be an efficient way for a person in his or her car to contact another person, or vice-versa. Perhaps you are involved in a traffic tie-up and need to reschedule an appointment, or you or someone else needs to be advised of an emergency. The obvious choice is a portable telephone that could be used over much greater distances than an ordinary cordless phone.

This chapter explains how mobile telephones have evolved over the years, and how cellular phones have made it possible for almost anyone to have telephone communications anywhere.

OBJECTIVES

When you complete this chapter, you will be able to:

- Describe the basic differences between older mobile telephones and more modern cellular phones.
- Describe the concept of a cellular system and the makeup of a cell.
- Explain how handoffs and roaming work.
- List the basic circuits of a cellular phone and the purpose of each.
- List the basic circuits of a cell site and the purpose of each.
- Describe the Personal Communications Service (PCS).
- Explain the meaning of the terms “dropout” and “dead zones.”

HISTORY OF MOBILE TELEPHONES

Commercial mobile telephone service began in 1946. The mobile portion of the system simply consisted of a transmitter and receiver which were bulky, expensive, and required relatively high-powered transmitters. To make a call, you called an operator on the radio who dialed the number for you and manually made the connection. This was a simplex system where you and the person you called had to take turns talking (as with most other 2-way radios). Due to the limited number of available frequencies, you often had to wait for a free frequency before you could make your call.

In 1963 an automated system became available so you could dial phone numbers yourself. Like the previous system, the available frequencies were limited.

In the late 1960s, the Improved Mobile Telephone System (IMTS) was born. This system operated in the VHF (152–153 MHz) and UHF (454–464 MHz) frequency ranges, which made them subject to interference from other mobile phones or systems, especially during certain atmospheric or "skip" conditions. This was particularly true with the VHF frequencies.

Because the number of frequencies was limited, so was the number of users. The result was congested frequencies, and potential subscribers had to wait for someone else to give up their mobile telephone before they could even get one. A typical system in a large city could only handle a couple of thousand subscribers, while many times that number of people wanted mobile phones.

The transmitter at the base station, which provided the connection between the radio link and the phone line, had an output power of about 200 or 300 watts and could generally cover an area with a radius of 25 or 30 miles. With this arrangement, base transmitters had to be at least 60 miles apart to reduce the possibility of interference, and this resulted in many areas that had no coverage.

Although this system worked well when the subscriber remained within his local service area, a problem existed when he traveled (roamed) into another service area. The subscriber had to notify the operator of the new service area in advance that he would be in the area. If someone wanted to call the roamer, they would have to use a special number and an operator would have to manually patch the call through.

A subscriber who travels into another service area other than his own is referred to as a *roamer*.

In 1983, AT&T designed a new cellular telephone system referred to as the Advanced Mobile Public Service (AMPS). This system is less expensive, more efficient, can handle many more subscribers, and dealt more easily with roamers. The remaining sections of this chapter explain how this system works in detail.

HOW CELLULAR TELEPHONES WORK

Because cellular telephones operate on radio frequencies, the Federal Communications Commission has assigned specific bands (ranges) of frequencies for cellular use (see Figure 8-1). Mobile telephones currently transmit between 824 and 849 MHz, while base stations transmit between 869 and 894 MHz. These frequency ranges are divided into channels, spaced 30 kHz apart, which results in 832 pairs of channels (previously there were 666 pairs). These channels are further divided into two 416-channel groups so that two competing companies can operate in the same area. One company is assigned one group (the A-carrier group) of frequencies, while the other company is assigned the other group (the B-carrier group) of frequencies.

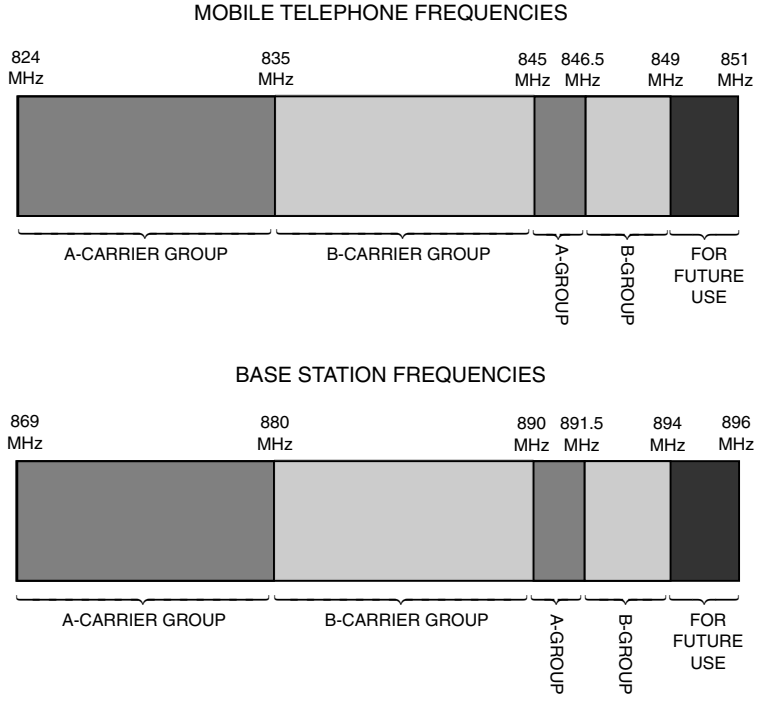

Figure 8-1

Cellular telephone frequencies.

Cellular transmitters are low powered and have limited range to reduce the possibility of interference to other transmitters. They use the FM (frequency modulation) mode for its improved audio fidelity and inherently noise-free operation as compared to the AM (amplitude modulation) mode. Currently, cellular systems use the AMPS (Advanced Mobile Phone Service) analog radio system invented in 1983 by AT&T. The frequency of the mobile telephone transmitter and the frequency of the base station transmitter are widely separated so that full-duplex operation can occur. Recall that full-duplex means that you can talk and listen at the same time.

Cellular telephone service areas are generally designed to cover a geographical area that be anywhere from a few blocks to about 20 miles in diameter. This service area is divided into seven cells as shown in Figure 8-2. Although the service areas are actually round with some overlapping as shown in Part A, they are usually shown with a hexagonal shape as shown in Part B for clarity. Each cell covers an area that is typically 3- to 5-miles wide, but may be up to 20 miles wide in wide-open areas that have few users. The actual size of a cell depends upon the number of users, terrain, nearby structures, weather conditions, etc. Since the high-frequency radio waves travel in straight lines, large objects like buildings and mountains can adversely affect cellular operation. Many closely-spaced cells provide you with the best possible telephone service.

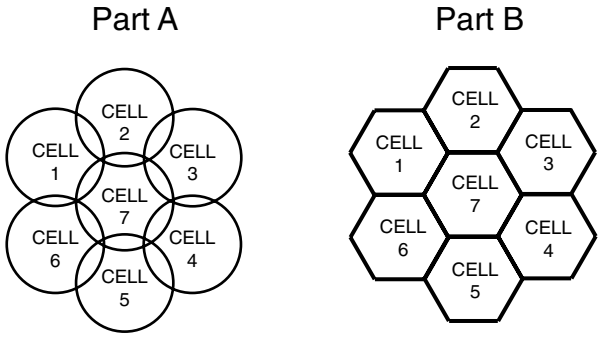

Figure 8-2
Cell grouping.

A *cell* is the basic unit that makes up a cellular system.

The number of allotted frequencies is divided among the cells in a system so that each cell is assigned a different group of channels (see Figure 8-3). Note that cells in other nearby systems are arranged so that no adjacent cells use the same channels. Cells using the same channels are separated enough to reduce the chance of interference. This technique makes very efficient use of the frequency spectrum by allowing the same frequencies to be used over and over again.

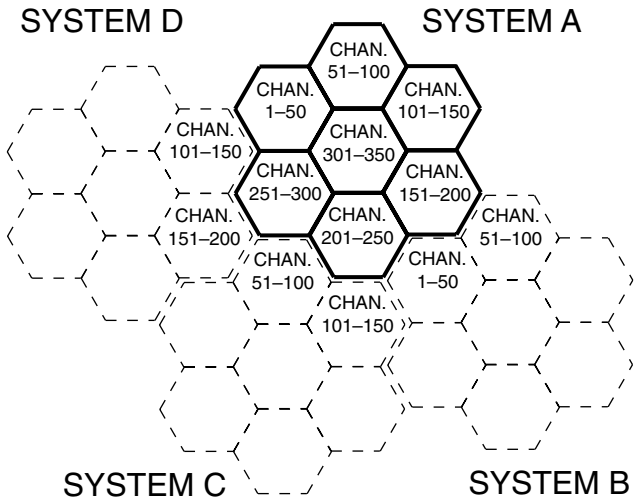

Figure 8-3

Frequency assignment.

In the example shown in Figure 8-3, 50 channels are assigned to each cell. Since one channel is used for the transmitter and one channel is used for the receiver, the cell is capable of handling 25 full-duplex calls at the same time.

Each cell contains an antenna system (usually three antennas arranged in a triangle at the top of a tower), a transmitter, a receiver, and a computerized control system. The control system of each of the seven cells is connected to a Mobile Telephone Switching Office (MTSO), as shown in Figure 8-4, which controls the operation of the entire system. The MTSO also performs the necessary interfacing between the cellular system and the central office, which connects to the PSTN (Public Service Telephone Network) through high-capacity trunk lines.

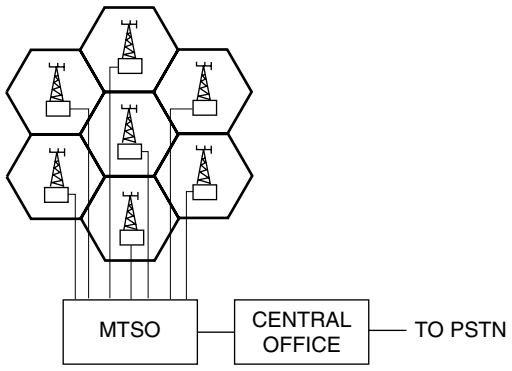

Figure 8-4
Wiring of cells.

In the event that a particular cell in a system becomes overloaded with users, engineers split the cell into two or more new cells as shown in Figure 8-5. Note that when a cell is split, the diameter of the resulting cells is 1/2 the diameter of the original cell. In Part A of the Figure, four new overlapping cells are created and the original cell site is not used. In Part B, the original cell site, although now smaller, is still used and six new cells are created. The method shown in Part A can handle four times more calls than the original cell, while the method shown in Part B can handle seven times more calls. Since cell sites are very expensive to build, only the minimum number of new cells are added to a system that can satisfactorily handle the increase in subscribers. The new cells use frequencies that provide the least amount of interference to and from nearby cells, and may use an array of directional antennas to alter the signal pattern. In addition, the new cells may be redesigned to use a lower-power transmitter and a lower antenna to reduce interference.

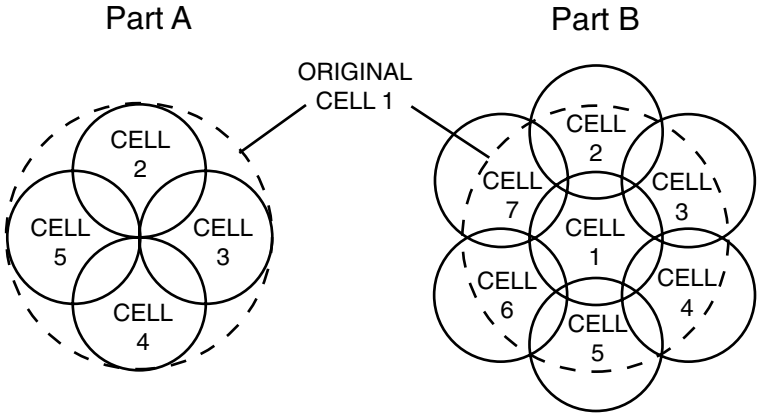

Figure 8-5
Two examples of cell splitting.

Cell splitting occurs when a single cell is divided into two or more new cells. In extremely overloaded areas, cells may be divided into several very small cells called *microcells*.

Registration and Tracking

All cellular base stations transmit data on a particular frequency that is referred to as a *control channel*. When you turn on a mobile cell phone, it's receiver scans through all of the channels and locks onto the base station that has the strongest signal. The mobile phone then transmits it's unique electronic serial number (ESN) and phone number to the base station. This information was previously stored in the phone's numeric assignment module (NAM) by the installer. Some cell phones have a dual-NAM feature so that they can register with two different cellular telephone systems.

Registration occurs when a mobile phone transmits its electronic serial number and phone number to a base station.

While the mobile phone is turned on, it reregisters with the base station every few minutes. This is necessary so the base station keeps track of the mobile's location in the event someone attempts to call it. In the event the mobile travels into an area that is better serviced by another base station, the MTSO directs the mobile phone and base stations to make the change. This is all done automatically by measuring the signal strength of the mobile, without the knowledge of the phone's owner.

All MTSOs in a particular system are connected together. If the mobile travels into an area that is controlled by a different MTSO, it changes to the new MTSO as well as a new base station.

Placing a Phone Call

The easiest way to understand how a cellular system handles phone calls is to follow a typical call through the system. The following paragraphs first describe what happens when a mobile phone makes a call, and then how the mobile phone receives a call.

To make a call, the mobile user dials the number he wants to call, checks the phone's display to make sure the number is correct, and then presses the Send button. This transmits the request to the base station on it's designated set-up channel. When a base station receives this request, it first selects two of it's unused channels (one for transmit and one for receive) and directs the mobile phone to switch to these channels. The call is then routed through the MTSO, its associated central office, and the PSTN to the number called. After this, the phone call proceeds like any other phone call. As the phone call continues, the MTSO directs other nearby base stations to measure the signal strength of the mobile. If one base station reports a better signal strength than the one being used, the MTSO will direct the mobile phone and current base station to hand-off the call to the new base station. This may occur many times during a conversation and generally occurs so fast (less than 1/10 of a second), that the persons involved in the conversation don't even know it happened.

When someone calls the mobile phone, the MTSO directs the appropriate base station to make the mobile phone ring. If the call is answered, conversation takes place as usual and may be handed-off as described above.

Roaming

Occasionally you will take your cellular telephone into a service area other than your own. This is referred to as *roaming*.

Since radio waves are invisible and many cell sites have irregularly-shaped signal coverage areas, you are not normally aware that you have roamed into another service area. The only way you can tell for sure that you are in another area is by looking at your cell phone's display. If the Roam indicator on your phone is lit constantly, your phone has determined that it is in another area. If the Roam indicator flashes, your phone has determined that it is in another area, and is monitoring a service (A-carrier or B-carrier) other than the one that it has been preprogrammed for. If you travel into an area that does not have cellular service, or is out of range of any cell sites, the No Service indicator on your phone will light.

Virtually all cell phones can automatically switch between A-carrier and B-carrier service. In the event you are in an area that is covered by both carriers, the service that has been preprogrammed in NAM by the installer has priority. Your phone also has provision so you can lock the phone to one service or the other. Locking your phone to one service may be the best choice because in many cases it can reduce the

cost of the service, especially when you roam into another area. However, if you roam into an area that is serviced by the opposite carrier, the No Service indicator will light.

It is fairly easy to make outgoing phone calls when you are in a service area other than your own. The majority of cell phone carriers have made reciprocal arrangements with other companies so that phone calls placed by roamers can be handled automatically. The main difference is that you generally must use the area code when you are not in your home service area. This is necessary because the same 7-digit phone number may be assigned to someone else in your new service area. Many carriers do not require you to prefix the area code with a 1 or 0, but other carriers may require it. In any case, a recording will advise you if you omit something when you dial a number.

Incoming calls when you are roaming can be more difficult than outgoing calls. At this time, a caller needs to know where you are and how to access the system in your area in order to contact you. If he simply dials your cell phone number by itself when you are in another area, he will probably hear a recording advising him that your phone is not in service (because your home system doesn't know where you are).

The following steps describe a procedure that is widely-used to call a roamer:

1. Dial the access number of the system in the roamer's area. A typical access number consists of the area code followed by 555-7626. Note that 7626 corresponds to the letters ROAM.

2. When you hear a tone, dial the roamer's **home** area code followed by the cell phone number. The area code is required because the roamer's cell phone number could possibly assigned to someone else in the roamer's new service area.

The cell phone will now ring, if its turned on, and conversation can proceed as usual.

THE CELLULAR PHONE

Cellular phones come in a variety of sizes and shapes. They can be permanently mounted in a vehicle, or small enough to carry in a pocket or purse. You can also obtain a headset/microphone accessory that features hands-free operation. The following discussion describes a typical installation in a car; a portable unit contains the same basic parts, but on a much smaller scale.

A mobile installation consists of a power source, a handset/control head, a radio/logic unit, and an antenna as shown in Figure 8-6.

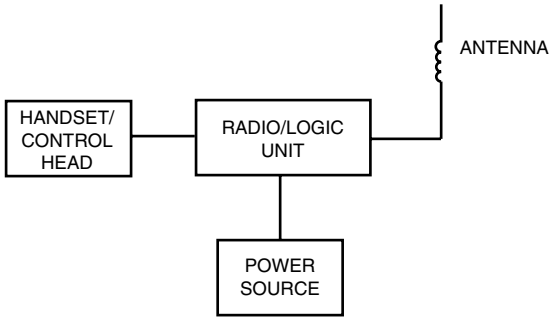

Figure 8-6

Block diagram of a mobile installation.

The car's battery usually provides the power source in a mobile installation. A cell phone that can be used both inside and outside of a vehicle may have a provision to plug into the cigarette lighter, and also contain its own rechargeable battery (nickel-cadmium or gel cell).

The handset/control head is the only part of the installation that needs to be near the user. It normally consists of a hand-held unit, about the size of a regular telephone handset (see Figure 8-7), and a holder that secures the hand-held unit in a convenient location when it is not in use. The handset contains a display and the pushbuttons necessary to check the status of the system and make and receive telephone calls. The handset is connected to the control head via a coiled-cord cable, while the control head is connected to the radio/logic unit via a multiwire cable.

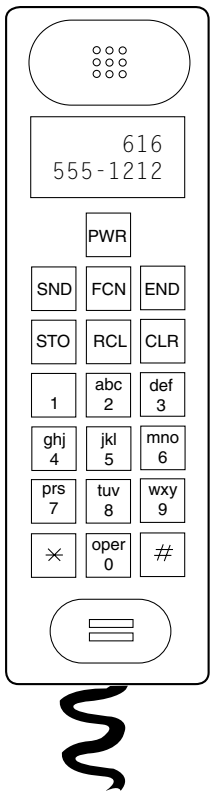

Figure 8-7
Typical cellular handset.

The radio/logic unit is the heart of the cell phone and consists of a transmitter, receiver, and a microprocessor-based control system. The transmitter and receiver provide the radio-frequency link between the cell phone and a cell site. They must each be capable of quickly switching to any of the 832 available cellular telephone frequencies. The control system is the brains of the cell phone. It maintains contact with a cell site by directing the transmitter and receiver to switch frequencies when required (when you begin a call and during a handoff), transmits the cell phone's correct ESN and NAM to the cell site, and adjusts the transmitter so it puts out only enough power to provide a reliable connection to a cell site.

The antenna is an important part of the cell phone installation, although it usually doesn't get the respect it deserves. It must radiate a good signal for a cell site to receive, and must be able to satisfactorily pick up the signal from the cell site. The most common cellular mobile antenna is the through-glass type (see Figure 8-8). A plate at the

bottom of this antenna sticks to the glass on the outside of a window and a pick-up box sticks to the inside of the window. The glass between these two units forms a capacitor and allows you to have an outside antenna on your vehicle without drilling holes or routing a cable through a door or trunk opening. Other antennas have a magnetic base that holds the antenna to a trunk lid or roof. The phasing coil in the antenna may have open turns like the one shown, or it may have a molded coil. The molded-style is used to prevent wind from whistling through the coil.

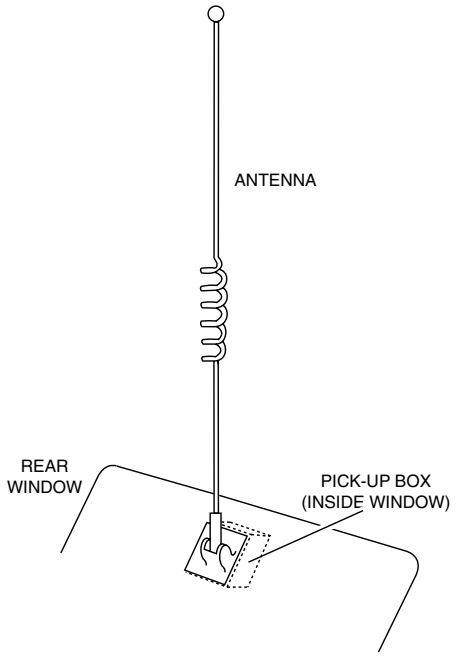

Figure 8-8

Through-glass cellular mobile antenna.

THE CELLULAR BASE STATION

A cellular base station, or cell site, forms the wireless link between a mobile cell phone and the regular telephone system. It consists of several transmitters and receivers, computerized control/switching circuits, and an antenna system as shown in Figure 8-9.

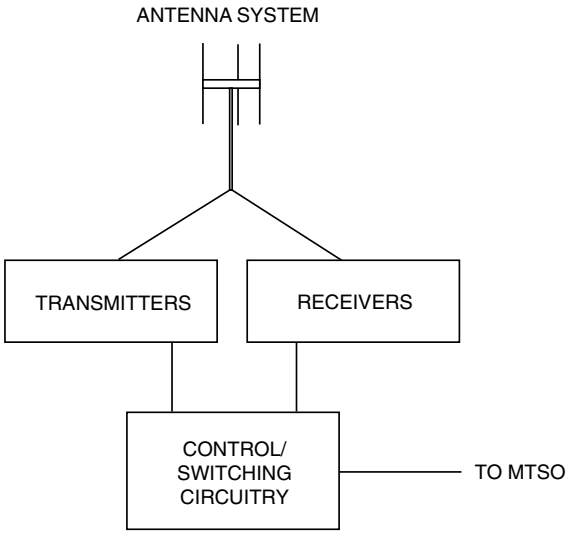

Figure 8-9

Block diagram of a cellular base station.

The number of transmitters and receivers used in a particular system depend upon the number of channels that have been assigned to the cell site. One transmitter and one receiver is required for each full-duplex conversation. The output power levels of the transmitters are adjusted so that they can cover the intended service area and not cause interference to other cell sites. Each receiver contains selective filtering to prevent the transmitters at the site from causing interference.

The computerized control/switching circuits form the command system of the cell site. This system measures the strength of incoming signals, performs channel changing, and controls hand-offs. It is responsible for everything that goes on in the cell site and must work together with the MTSO and control/switching circuits at other cell sites in the system.

The antenna system typically consists of three vertical elements arranged in a triangular configuration. Each element consists of one antenna for receiving and one for transmitting. The spacing between the elements and close proximity to the support structure (such as a tower) make the antennas directional.

CELLULAR PROBLEMS

Although cellular telephone is a great improvement over older systems, it still has a few problems. The major problems are dropouts, dead spots, and security.

Dropouts occur when there is a momentary loss of the received and/or transmitted signal. Because cellular telephone uses radio waves in the 800 to 900 MHz range, they travel in straight lines which can be affected in many ways. Moisture in the air, such as from rain or fog, can easily weaken the radio waves. They can also be reflected or blocked by hills, mountains, or buildings. In some cases, a cell phone may receive several signals at the same time, one direct and one or more reflected. When this happens, a phenomenon called "multipath" occurs where the signals may mix and cancel out. Dropouts range from an occasional interruption to a complete loss of signal that causes you to become disconnected.

Dead spots are small or large areas where there is no cellular radio reception at all. Dead spots can be caused by buildings, hills, mountains, or thickly wooded areas. In addition, if the timing between two multipath signals is just right, they will cancel out and result in no reception. When you encounter a dead spot, the display on your cell phone may indicate "No Service", just like it does when you are in an area where cellular service is not available.

Since cellular phones use radio waves to operate, security is an important concern. Many radio frequency scanners sold in recent years are capable of receiving cellular signals, while some others that have cellular frequencies blocked out may be easily modified. Also, older television sets may be able to receive cellular frequencies on the upper UHF channels. Tracking a cellular call when it is handed off to another cell (and therefore another frequency) may be somewhat difficult, but it is still best not to say anything over a cell phone that you wouldn't say in public.

Another security concern is your cell phone's ESN. Although ESNs are hard to change without sophisticated equipment, high-tech thieves may have access to the equipment to clone your cell phone. When they do this, their cloned phone will act just like yours and you may be billed for calls you didn't make. Some modern cellular systems help protect you from this piracy by watching for two cell phones using the same ESN.

PERSONAL COMMUNICATIONS SERVICE (PCS)

The previous sections of this chapter described the original cellular telephone system. That system was based on analog technology, and is often referred to as the first generation of cellular telephone. As wireless phones became more and more popular, the existing systems soon became overloaded, especially in larger cities. This was temporarily solved by splitting cells as necessary to accommodate more users. Unfortunately there is a practical limit as to how many cells you can have in a particular area, and how small they can be. Because the frequencies used by cells in one group are reused in the adjacent groups, and as the cells become closer to each other, the more likely you are to have interference between two nearby cells using the same frequency. In addition, cells are expensive to construct, and sometimes impossible to put where you need them most.

Second generation cellular telephone systems use digital technology. These systems are more immune to co-channel and adjacent-channel interference, work well with both voice and data transmissions, provide greater security, and increase system capacity by allowing several voice transmissions to be carried over a single carrier (channel). Although digital cellular sounds like a cure-all, it has its disadvantages. Digital is more expensive and has less coverage than analog. In addition, because there is no digital standard, a digital phone may not work while roaming due to incompatible systems. Today, a new digital cellular system referred to as PCS (Personal Communications Service) is being built. This the subject of the remaining part of this chapter.

Description

PCS is the newest digital cellular technology. The original digital cellular systems used digital technology in existing analog cellular networks. PCS, however, is completely digital and works with both voice and data transmission.

You can think of a PCS portable handset as several devices in one small package. In addition to making and receiving telephone calls, its display allows you to use it to receive pages, weather and traffic reports, faxes, news, sports scores, and for 2-way messaging. Because the owner of a PCS handset must pay for incoming as well as outgoing calls, some PCS phones feature caller-ID so the user can decide whether he or she wants to answer the call.

The interest in PCS is growing at an enormous rate. Have you noticed towers like the one shown in Figure 8-10 popping up all over the place, especially near expressways? These are PCS towers.

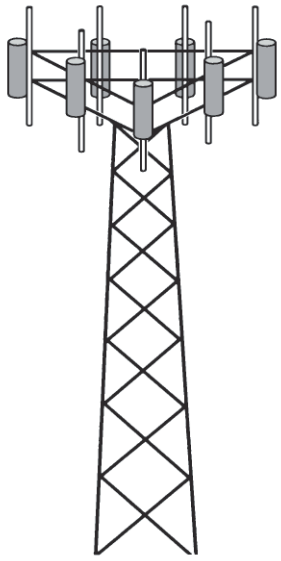

Figure 8-10

Typical PCS tower.

Technical Aspects

The frequency spectrum the FCC has allocated for PCS is divided into three basic categories which are referred to as broadband, narrowband, and unlicensed.

The narrowband category operates in the 901 to 902 MHz, 930 to 931 MHz, and 940 to 941 MHz bands. It is used primarily for advanced paging and messaging.

The broadband and unlicensed categories operate on much higher frequencies between 1850 and 1990 MHz. This band of frequencies is divided up into sections as shown in Figure 8-11 on the next page.

As indicated, the 60 MHz section between 1850 MHz and 1910 MHz is used for the radio link from the handset to the cell, and the 60 MHz section between 1930 MHz and 1990 MHz is used for the radio link from the cell to the handset.

The 20 MHz unlicensed section between 1910 and 1930 MHz is used for short-range communications purposes such as wireless LANs in offices. They use very low-power transmitters and the transmissions are short.

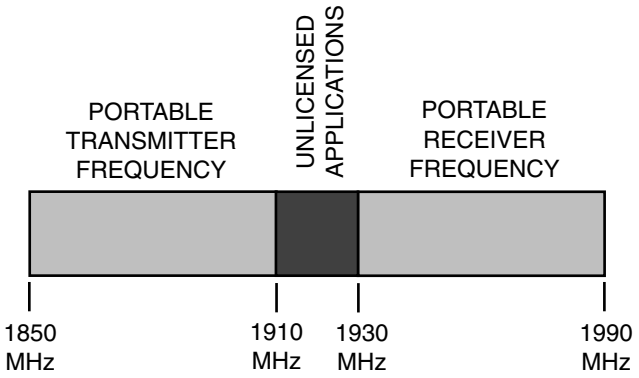

Figure 8-11

The PCS band between 1850 and 1990 MHz.

Unfortunately, there are three different incompatible standards for PCS. These are TDMA (Time Division Multiple Access), CDMA (Code Division Multiple Access), and GSM (Global System for Mobile Communication).

With TDMA, the users on a given channel are divided into time slots, and each user is assigned a specific slot. During a particular period of time, one user transmits during the first slot, another user transmits during the next slot, etc. This all takes place very quickly, so the user doesn't know its happening.

With CDMA, the users on a given channel transmit at the same time, and are separated by their encoding scheme. CDMA uses a very wide channel and uses a technique called "spread spectrum" which spreads out the digital bits. This is extremely hard to detect because it just sounds like noise.

GSM also uses TDMA, but over a much wider bandwidth. Instead of using 25 or 30 kHz wide channels, like other digital standards use, GSM uses a 200 kHz channel. This helps reduce fading and provides better performance at higher data rates. Europe has adopted GSM as their standard so that PCS phones which use this technology can roam from one country to another. Many PCS systems in the United States also use this system.

Advantages of PCS

Because PCS phones are completely digital, their transmissions are much more secure. The phones are much smaller, cost less, and use less power. Less power consumption allows them to run longer. PCS cells are smaller and frequencies can be reused more often, so the number of phones which can be used in a particular area increases. 1900 MHz PCS transmissions also penetrate buildings better than 800 MHz cellular phones.

Disadvantages of PCS

The main problem with PCS is that because it has not yet saturated the United States like 800 MHz cellular has, its coverage area is much more limited. PCS phones work only up to 4-miles from a base station while 800 MHz cellular phones work up to 10 miles. Therefore, you need more cells to provide comparable coverage. Cell sites are expensive and require a lot of planning. In addition, some PCS systems are running into a lot of opposition from local planning committees who do not want the towers in their neighborhoods.

Future Outlook

As more PCS cell sites become operational, PCS phones will experience improvement in their coverage areas. This should reduce the number of drop-outs. Because PCS phones are capable of more than just placing and receiving phone calls, they should rapidly become more popular than other types of cellular telephone systems.

As technology improves, wireless phones will communicate directly through satellites instead of through ground-based stations.

Recent FCC Action

Many people obtain cellular telephones mainly so they can call for help in an emergency. However, this presents a major problem. With wired telephone systems, caller ID can help local authorities identify and locate emergency callers. But the portable nature of cellular phones makes this difficult, especially in cases where the caller is in an unfamiliar area and does not know exactly where they are.

To make it easier to locate 911 emergency callers, and reduce the response time, the FCC has issued a 2-part order. The first part, which began in the spring of 1998, required the following:

- Cellular carriers must accept 911 calls whether or not the caller subcribes to their system.

- The caller's number and identification of the cell site involved must be sent to the public safety access point (the personel and equipment which handles 911 calls).

- The cellular phone number is sent to the public safety access point so they can call the cellular phone in the event the call is dropped.

The second part, to be in place by October 1, 2001 requires the following:

- Cellular providers must be able to pinpoint the longitude and latitude of the caller's location within 125 meters (137 feet), at least 67% of the time.

- The above applies to all cellular calls, whether they are made while roaming or in their home area. It also applies to handsets manufactured before these rules went into effect.

SUMMARY

In this chapter, you learned how mobile telephones have advanced from a very crude system that required operator intervention to a more modern cellular system that is computer controlled and fully automatic. Today's cellular phones are very affordable and small enough that almost anyone can carry one with them and use it just about anyplace.

Second, you learned the theory behind the cellular system and how cells are arranged to provide service to a particular service area. When a cell becomes overloaded, it can be divided into two or more cells to ease congestion. Frequencies are chosen and assigned to each cell to prevent interference to other cells in the system and nearby cells in other systems.

Third, you learned how cell phones are tracked, and handed off from cell to cell and how outgoing and incoming phone calls are handled.

Fourth, you learned what makes up a cellular phone and base station and the function of each major section.

Next, you learned how dropouts and dead spots can affect your cell phone's operation, and how security is of some concern.

Finally, you learned about PCS, which is a new wireless phone system which offers many more features than ordinary cellular systems.

SELF-TEST REVIEW

1. What frequency ranges do cellular telephones use?

   A. 152–153 MHz.
   B. 454–464 MHz.
   C. 824–849 and 869–894 MHz.
   D. None of the above.

2. How many pairs of channels is assigned to each cellular company in a given area?

   A. 50
   B. 208
   C. 416
   D. 832

3. What are persons called when they use a cellular phone in a service area other then their own?

   A. Roamers.
   B. Handoffs.
   C. Pirates.
   D. Eavesdroppers.

4. How many cells are typically grouped together in a system?

   A. 2
   B. 5
   C. 7
   D. 8

5. When a cell is split into two or more new cells, the diameter of the new cells are:

   A. the same diameter as the original cell.
   B. half the diameter of the original cell.
   C. twice the diameter of the original cell.
   D. the same diameter as the original cell divided by the number of cells.

6. What occurs when a mobile cell phone transmits its electronic serial number and phone number to a cellular base station at power-up?

   A. Registration.
   B. A handoff.
   C. An outgoing call is placed.
   D. An incoming call is received.

7. How can you tell when you have roamed into an area that is serviced by a carrier other than the one it has been preprogrammed for?

   A. The Roam indicator will light constantly.
   B. The No Service indicator will light constantly.
   C. The Roam indicator will flash.
   D. There is no way to tell.

8. Which of the following is not part of a cell phone mobile installation?

   A. Handset/control head.
   B. Radio/logic unit.
   C. Antenna.
   D. MTSO.

9. How many vertical elements generally make up a cellular base station's antenna system?

   A. 1
   B. 2
   C. 3
   D. 6

10. Which of the following can cause dead spots and dropouts?

    A. Hills.
    B. Mountains.
    C. Buildings.
    D. All of the above.

11. Moisture in the air can affect cellular telephone operation.

    A. True.
    B. False.

12. The frequencies used by cellular phones cannot be intercepted.

    A. True.
    B. False.

13. Which of the following frequency bands is used for broadband and unlicensed PCS operation?

    A. 901 – 902 MHz.
    B. 930 – 931 MHz.
    C. 940 – 941 MHz.
    D. 1850 – 1990 MHz.

14. Which of the following is considered an advantage of PCS phones?

    A. Smaller size.
    B. Lower battery consumption.
    C. Transmissions are more secure.
    D. All of the above.

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